

APPENDIX A
SAMPLE PROBLEMS

APPENDIX A SAMPLE PROBLEMS

A-1. Sample source and process selection. A facility has been proposed near El Paso, Texas. The final facility population is set at 100 full-time resident personnel. Use TM 5813-1 to obtain water consumption per day. The calculation is as follows:

$$100 \text{ Persons} \times \frac{150 \text{ gallons}}{\text{day Person}} \times \frac{(\text{Capacity})}{(\text{Factor})}$$

The nearest flowing river is the Rio Grande, which is 100 miles from the proposed site. Surface water in shallow lakes is also available. Investigations at one location indicate that the lake is much saltier than seawater. A groundwater literature review indicates that several brackish water aquifers exist in the area.

The assumed site data are summarized below:

- 1-Surface lake water is more saline than sea water.
- 2-River water is more than 100 miles away.
- 3-Available brackish water is only slightly saline.
- 4-Solar energy is available.
- 5-Pond evaporation of brine would be about 0.7 multiplied by net pan evaporation (86 inches per year) = 60 inches per year.
- 6-Power lines are remote. A natural gas supply is available at the proposed site. Electricity for the facility could be produced by natural gas engines.

Saline Lake Water

The use of table 4-1 indicates that Rule 1 will apply to this water source (see fig. A-1, Sample use of table 4-1).

Rule 1 states that water saltier than sea water is probably not economical for desalination. A total dissolved solids determination should be run on the lake water to verify excessive salinity.

Assume that the laboratory analyses recommended in table 4-1 were performed and the following was obtained:

Saline lake water
Total dissolved solids 70,000 milligrams per liter

Now use table 4-2 where Rule 1 is applicable. Rule 1 states that if this water must be used, thermal distillation is the only possible process. (See fig. A-2, Sample use of table 4-2). Since alternate brackish water sources are available, this water source is rejected.

Brackish Groundwater

The use of table 4-1 indicates that Rule 6 or Rule 7 will apply to this water source (see fig. A-1).

Rule 6 states that the most economical method to obtain drinking water from brackish water is through reverse osmosis, regardless of how electricity is to be generated. Analyses of total dissolved solids, calcium, sulfate, carbonate, pH, bacterial count, silt density index, turbidity, and low-level oil and grease (less than 1 milligram per liter), as well as the other tests called for in Appendix B, should be performed on test-well water sample.

Rule 7 states that electrodialysis reversal should be investigated for slightly saline water, regardless of electric or steam costs. A total dissolved solids determination, full ionic breakdown, bacterial count, turbidity, and the other tests listed in Appendix B should be done on these test-well samples.

In one area of the site assume that a 230-foot-deep test well is drilled and that the laboratory analyses recommended in table 4-1, Rule 6, were performed and the following data shown in figure A-3 were obtained:

The following data were extracted from the laboratory analysis and bacterial plate count:

230-foot-deep well

total dissolved solids 5,000 milligrams per liter

Ca⁺⁺ 150 milligrams per liter

SO₄⁻ 300 milligrams per liter

CO₃⁻ milligrams per liter

HCO₃⁻ 172 milligrams per liter

Source: U.S. Army Corps of Engineers







RULE	A	B	C	D	E	F
	If the freshest source of water is:	And if the desired output water will be:	And if electricity is to be generated:	And if the projected cost ratio of $\frac{254^{\circ}\text{F Steam}}{\text{Electricity}}$	Then investigate the cost of:	And have the following tests performed:
1	More salty than sea water 	Potable water			Transportation of fresher water: distillation can be used but at great expense	TDS
2	Sea water 	High-pressure boiler feed water	By steam turbine		Distillation followed by ion exchange	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH refer to water testing requirements in Appendix B
3	Sea water	Potable water	By steam turbine	Greater than $\frac{10 \times 10^6 \text{ BTU}}{1 \text{ kwh}}$	Thermal distillation with or without vapor compression	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH
4	Sea water	Potable water	By internal combustion engine		Vapor compression distillation and waste heat	TDS, bacterial count, turbidity
5	Sea water	Potable water	No	Less than $\frac{10 \times 10^6 \text{ BTU}}{1 \text{ kwh}}$	Reverse osmosis	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH, bacterial count, silt density index, turbidity, oil & grease refer to list for reverse osmosis, Appendix B
6	Brackish water	Potable water			Reverse osmosis	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH, bacterial count, silt density index, turbidity, oil & grease
7	Slightly saline brackish water	Potable water			Electrodialysis reversal	TDS, full ionic breakdown, bacterial count, turbidity refer to list for electrodialysis reversal, Appendix B

Figure A-1. Sample use of table 4-1

Source U.S. Army Corps of Engineers

RULE	A	B	C	D	E	F
	If the feed water TDS is (mg/liter):	And if the raw feed water suspended solids are:	And if the product of the $[Ca^{++}][SO_4^{--}]$ moles ² /liter ² is in the reject brine (see sample problem A-3)	And if the oil and grease in the raw feed water is:	Then investigate the cost of:	And have the following pretreatment processes investigated for effectiveness:
1	Greater than 50,000 				Transportation of fresher water; distillation of this water is extremely expensive	Precipitation of less soluble salts
2	Between 20,000 - 50,000	Over 20 NTU	Considerably less than 2×10^{-4}	Greater than 10 mg/liter	Reverse osmosis or distillation and steam and electricity	Alum jar tests, pH adjustment 10-micron or smaller filter plugging
3	Between 20,000 - 50,000 	Over 1 NTU		Less than 10 mg/liter	Reverse osmosis	Alum jar tests 10-micron or smaller filter plugging UV sterilization
4	Between 20,000 - 50,000 	Less than 1 NTU SDI greater than 3		Less than 10 mg/liter	Spiral-wound membrane reverse osmosis	pH adjustment, UV sterilization, chlorine disinfection, chlorine residual
5	Between 20,000 - 50,000 	SDI under 3		Less than 10 mg/liter	Hollow fine-fiber membrane reverse osmosis	10-micron or smaller filter test, UV sterilization
6	Between 3,000 - 20,000	Over 1,000 mg/liter	Considerably less than 2×10^{-4}	Greater than 10 mg/liter	Distillation	pH adjustment, alum jar test
7	Between 3,000 - 20,000			Less than 10 mg/liter	Reverse osmosis	pH adjustment, alum jar test, silt density index, UV sterilization
8	Between 500 - 4,000				Electrodialysis reversal	pH adjustment, alum jar test, 10-micron filter plugging, chlorine disinfection

*Note: Only 500 mg/liter potable water is considered after table 4-1.

Figure A-2. Sample use of table 4-2.

PHYSICAL AND CHEMICAL ANALYSIS OF WATER

1. Sample Number: Sample Problem A-1a 2. Date and Hour Collected: 7-13-82
 3. From: El Paso, Texas 11:00 AM
 4. To:
 5. Sample Location and Description Well 1 (230-foot deep well)
 6. Requested By:
 7. Collected By: Mr. William Digger
 8. Preservation: Reason for Request: Water Source Evaluation

LABORATORY REPORT						
X	ITEM	UNITS	RESULTS	X	ITEM	RESULTS, mg/l
X	CO ₂	mg/l	0.0	X	Ca	150
X	O ₂ (dissolved)	"	0.0	X	Mg	60
X	H ₂ S	"	<0.1	X	Na and K	1650
X	PH	units	8.5	X	OH	0.0
X	Temp.	°F/°C	58/14.4	X	HCO ₃	172
X	Color	units	None	X	CO ₃	3
X	Turbidity (3)	NTU	0.01 SDI = 1	X	SO ₄	300
X	*P Alkalinity	mg/l	2.5	X	Cl	2640
X	*MO Alkalinity	"	146	X	NO ₃	3.0
X	*Total Hardness	"	622	X	Fe (total)	<0.01
X	*Non-Carbonate Hardness	"	476	X	Mn	<0.01
X	*Carbonate Hardness	"	146	X	SiO ₂	16
X	Total Dissolved Solids	"	5,000	X	F	2.8
X	Specific Conductance	μmhos	9,000	X	As	<0.001
	Others (specify as req'd)			X	Se	<0.001
X	Cl ₂ (1)		<1.0	X	Pb	<0.001
X	PO		1.0	X	B	<0.2
X	10 mg Oil/Grease (2)		<1.0	X	Cu	<0.01
X	Molybdenate Reactive Silica	PPM	15	X	Zn	<0.1
X	Molybdenate Non-Reactive Silica	PPM	1	X	Cr (+6)	<0.0001
X	Phenolic Compounds (PPB)	PPM	<0.0001	X	Cd	<0.0001
	*As CaCO ₃			X	CN	<0.0001

X Indicate if required

- (1) 10 Minute Demand.
- (2) Utilize a 50 fold, low temperature, low pressure concentrating technique to verify <10 mg/l Oil & Grease.
- (3) A Silt Density Index determination must be made on all waters with a turbidity of less than 2 NTU.

Figure A-3. Water analysis (sample problem A-1a).

Source: U.S. Army Corps of Engineers

RULE	A	B	C	D	E	F	G
	If the treated feed water salinity (mg/l) will be (see note):	And the cost ratio of 264°F steam 1 kwh electricity will be:	Alkaline earths on the raw water are such that (see sample problem A-3):	And the treated suspended solids are:	And the designated chlorine residual is:	Then investigate the cost of:	With the following pre- and post-treatment technique costs:
1	Between 20,000 - 50,000		Within 66% of saturation	Less than 1 NTU but SDI greater than 3	0.0 mg/liter	Spiral-wound membrane reverse osmosis	Whatever treatment is necessary to produce D and E
2	Between 20,000 - 50,000		Within 66% of saturation	SDI less than 3	0.0 mg/liter	Hollow fine-fiber membrane reverse osmosis	Whatever treatment is necessary to produce D and E
3	Between 20,000 - 50,000			Less than 1 NTU	Between 1.0 and 0.0 mg/l	Chlorine-resistant membrane reverse osmosis	Whatever treatment is necessary to produce D and E
4	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh	Within 50% of saturation	Greater than 1 NTU	More than 1 mg/l	Some form of distillation under 185°F	Anti-scalent
5	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh		Greater than 1 NTU	More than 1 mg/l	Some form of distillation	Acid feed (hydrochloric is best)
6	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh	$[Ca^{++}]$ multiplied by $[SO_4^{--}]$ Well Under 2×10^{-6}	Greater than 1 NTU	More than 1 mg/l	Some form of distillation	No pretreatment for calcium sulfate scale control
7	Between 3,000 - 20,000			Less than 1 NTU but SDI greater than 3	Less than 1.0 mg/l**	Brackish water spiral-wound membrane reverse osmosis	Whatever treatment is necessary to produce D and E
8	Between 3,000 - 20,000			SDI less than 3	Less than 1.0 mg/l**	Brackish water hollow fine-fiber membrane reverse osmosis	Whatever treatment is necessary to produce D and E
9	Between 500 - 4,000; and especially when expected to vary by more than 15%			Will not plug 10-micron filter	0.0 mg/l**	Electrodialysis reversal	Turbidity removal To 1 NTU and disinfection to less than 1/100 ml.
10	Is stable at some value between 500 - 1000			SDI less than 3	Less than 1.0 mg/l**	Low pressure/high flux membrane reverse osmosis	Whatever treatment is necessary to produce D and E

*Note: Only 500 mg/l of potable water is considered after table 4-1.

Desalination of water more saline than 50,000 mg/liter is not considered after table 4-2.

**For chlorine-resistant membranes only, and for polyaromatic amide membranes, 0.0 mg/l.

Figure A-4. Sample use of table 4-3.

pH 8.5
 Bacterial count 0/100 milliliter (membrane filter technique)
 Silt density index 1
 Turbidity less than 0.01 nephelometric turbidity unit
 Oil and grease less than 1 milligrams per liter

In table 4-2, Rule 7 is applicable (see fig. A-2). Rule 7 states that reverse osmosis processes should be investigated. The low level of silt density index precludes the necessity of an alum jar test.

Use table 4-3 showing that Rule 8 applies (see fig. A-4). Rule 8 states that hollow fine-fiber reverse osmosis specifications should be prepared. No specific pretreatment process is necessary.

In another area of the site a 500-foot test well was drilled. The driller's report indicated that this water had a slight saline taste. Table 4-1, Rule 7 applies (see fig. A-1).

Rule 7 states that electrodialysis reversal should be investigated for slightly saline water, regardless of electric or steam costs. The recommended laboratory analyses are: total dissolved solids, a full ionic breakdown, bacterial count, turbidity, and the other tests for electrodialysis-reversal feed waters listed in Appendix B.

Assume that the laboratory analyses of this water sample give the following data shown in figure A-5.

The following data were extracted from the laboratory analysis and bacterial plate counts:

500-foot-deep well
 total dissolved solids 1,000 milligrams per liter
 Ca^{++} 100 milligrams per liter as CaCO_3
 Mg^{++} 7 milligrams per liter
 SO_4^{--} 240 milligrams per liter
 CO_3^{--} 0 milligrams per liter
 HCO_3^- 21 milligrams per liter
 Cl^- 389 milligrams per liter
 Na^+ 326 milligrams per liter
 Bacterial count 0/100 milliliter (membrane filter technique)
 Turbidity less than 0.01 nephelometric turbidity unit

Table 4-2, Rule 8 applies (see fig. A-2). Rule 8 states that electrodialysis reversal should be investigated. The low level of turbidity precludes the use of an alum jar test. The low salinity of this sample indicates this to be a superior quality brackish water source.

Application of the preliminary process selection information with table 4-3 results in two possible final process selections. Both Rule 9 and Rule 10 are applicable to this water source. (See fig. A-4)

Rule 9 states that low-pressure high-rate reverse osmosis specifications should be prepared, with antiscalants to be recommended.

Rule 10 states that electrodialysis-reversal specifications should be prepared.

A final decision should be based on the probability of the total dissolved solids fluctuating by more than approximately 15 percent.

Assume a fourth water source was also investigated at this same site. A shallow 32-foot test well was drilled. A preliminary inspection indicated this water was slightly saline and foul tasting with a strong rotten egg smell.

Use of table 4-1 indicates that Rule 6 and Rule 7 may apply (see fig. A-1). Rule 6 states that the most economical method to obtain drinking water from brackish water is through reverse osmosis, regardless of how electricity is to be generated. Analyses of total dissolved solids, calcium, sulfate, carbonate, pH, bacterial count, silt density index, turbidity, low-level oil and grease (below 1 milligram per liter), and any other tests called for in Appendix B should be performed on test-well water samples.

Rule 7 states that for slightly saline water electrodialysis reversal is the most economical method to obtain potable water from brackish water. Analysis of total dissolved solids, a full ionic breakdown, bacterial count, turbidity, and any other tests called for in Appendix B should be performed.

The laboratory analyses of this water sample give the following data shown in figure A-6:

PHYSICAL AND CHEMICAL ANALYSIS OF WATER

1. Sample Number: Sample Problem A-1b 2. Date and Hour Collected: 7-13-82
 3. From: El Paso, Tx 10:00 AM
 4. To:
 5. Sample Location and Description Well 2 (500-foot deep well) (Ground water)
 6. Requested By:
 7. Collected By: Mr. William Duggem
 8. Preservation: Reason for Request: Water Source Evaluation

LABORATORY REPORT						
X	ITEM	UNITS	RESULTS	X	ITEM	RESULTS, mg/l
X	CO ₂ (1) when fresh from well	mg/l	0	X	Ca	40
X	O ₂ (dissolved)	"	0.0	X	Mg	7
X	H ₂ S	"	<0.1	X	Na and K	326
X	PH	units	<0.1	X	OH	0.0
X	Temp.	°F/°C	55/13	X	HCO ₃	21
X	Color	units	None	X	CO ₃	0.0
X	Turbidity (3)	NTU	<0.01 SDI=1	X	SO ₄	240
X	*P Alkalinity	mg/l	0.0	X	Cl	384
X	*MO Alkalinity	"	17	X	NO ₃	1.0
X	*Total Hardness	"	129	X	Fe (total)	<0.01
X	*Non-Carbonate Hardness	"	112	X	Mn	0.1
X	*Carbonate Hardness	"	17	X	SiO ₂	30
X	Total Dissolved Solids	"	1,000	X	F	0.5
X	Specific Conductance	µmhos	1,800	X	As	<0.001
	Others (specify as req'd)			X	Se	<0.5
X	PO	PPM	<0.1	X	Pb	<0.001
X	10 mg Oil/Grease (2)	PPM	<1.0	X	B	<0.2
X	Molybdenate Reactive Silica	PPM	29	X	Cu	<0.01
X	Molybdenate Non-Reactive Silica	PPM	1	X	Zn	<0.1
X	Bacterial Count TPC		<0.01/100ml	X	Cr (+6)	<0.0001
X	Phenolic Compounds(PPB)		<0.0001	X	Cd	<0.0001
	*As CaCO ₃ Cl ₂ (2)	PPM	<0.1	X	CN	<0.0001

X Indicate if required

- (1) 10 Minute Demand.
- (2) Utilize a 50 fold, low temperature, low pressure concentrating technique to verify <10 mg/l Oil & Grease.
- (3) A Silt Density Index determination must be made on all waters with a turbidity of less than 2 NTU.

Figure A-5. Water analysis (sample problem A-1b).

PHYSICAL AND CHEMICAL ANALYSIS OF WATER

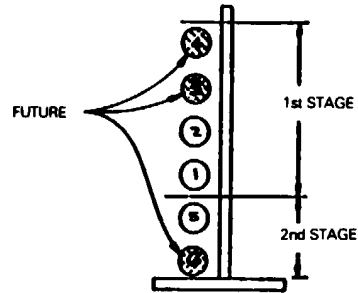
1. Sample Number: *Sample Problem A-1c* 2. Date and Hour Collected: *7-13-82*
 3. From: *El Paso, Texas* 9:00 AM
 4. To:
 5. Sample Location and Description *Well 3 (32-foot deep well)*
 6. Requested By:
 7. Collected By: *Mv. William Digger*
 8. Preservation: Reason for Request: *Water Source Evaluation*

LABORATORY REPORT						
X	ITEM	UNITS	RESULTS	X	ITEM	RESULTS, mg/l
X	CO ₂	mg/l	2	X	Ca	20
X	O ₂ (dissolved)	"	0	X	Mg	64
X	H ₂ S	"	> 300	X	Na and K	1368
X	PH	units	5.0	X	OH	0
X	Temp.	°F/°C	60/15.6	X	HCO ₃	0
X	Color	units	Brown To Red Absorbance = .5 at 400 nm	X	CO ₃	0
X	Turbidity	NTU	115	X	SO ₄	> 1000
X	*P Alkalinity	mg/l	0.0	X	Cl	1500
X	*MO Alkalinity	"	0.0	X	NO ₃	< 0.01
X	*Total Hardness	"	313	X	Fe (total)	< 0.0001
X	*Non-Carbonate Hardness	"	313	X	Mn	< 0.0001
X	*Carbonate Hardness	"	None CPH had dropped below 4.3 during handling	X	SiO ₂	< 0.1
X	Total Dissolved Solids	"	4,000	X	F	< 0.001
X	Specific Conductance	μmhos	6,000	X	As	< 0.001
	Others (specify as req'd)			X	Se	1.0
X	PO	PPM	< 1	X	Pb	< 0.0001
X	10 mg/L Oil/Grease	PPM	100	X	B	< 0.2
X	Molybdenate Reactive Silica	PPM	< 0.1	X	Cu	< 0.01
X	Molybdenate Non- Reactive Silica	PPM	< 0.1	X	Zn	< 0.1
X	Phenolic Compounds (PPB)	PPM	< 0.0001	X	Cr (+6)	< 0.0001
X	Cl ₂ demand Calculated from H ₂ S	PPM	> 2800	X	Cd	< 0.0001
	*As CaCO ₃			X	CN	< 0.0001

X Indicate if required

- (1) 10 Minute Demand.
- (2) Utilize a 50 fold, low temperature, low pressure concentrating technique to verify < 10 mg/l Oil & Grease.
- (3) A Silt Density Index determination must be made on all waters with a turbidity of less than 2 NTU.

Figure A-6. Water analysis (sample problem A-1c).



VESSEL PLACEMENT FOR
STAGING ARRANGEMENT

NOTE. WHEN POSITIONING THE PERMEATORS
FOLLOW NUMERICAL ORDER AS INDICATED
ABOVE

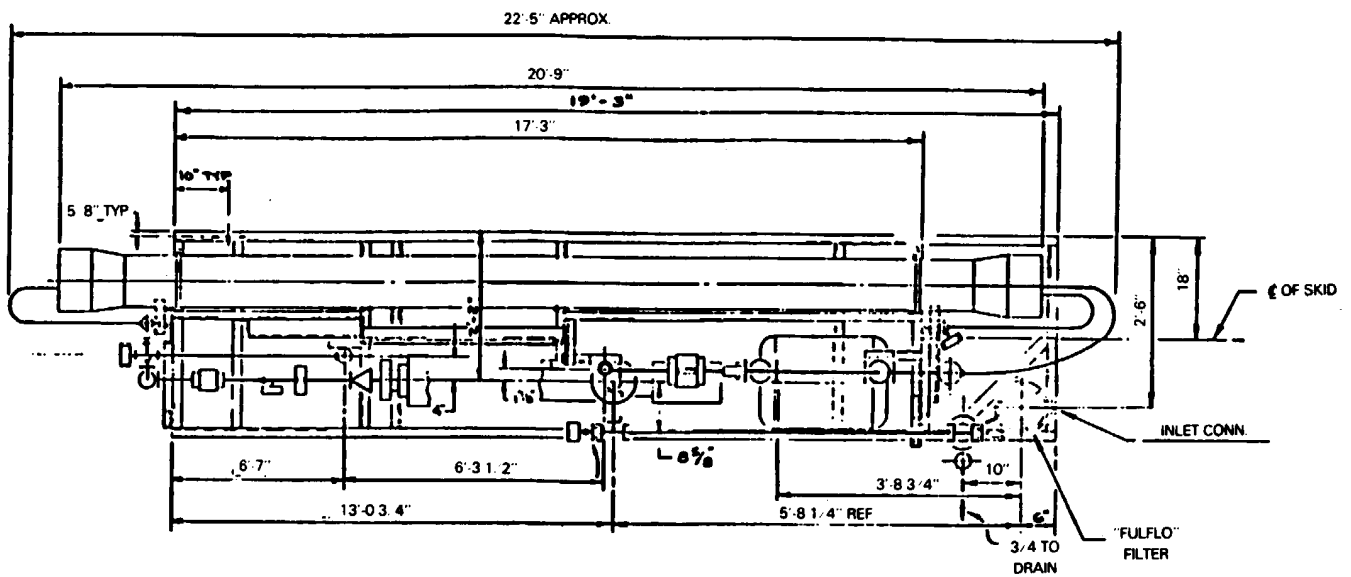


Figure A-7. Low Pressure Reverse Osmosis System.

Source: The Permutit Co., Inc.

The following data were extracted from laboratory analysis and bacterial plate counts:

32-foot-deep well

total dissolved solids 4,000 milligrams per liter

Ca^{++} 50 milligrams per liter as CaCO_3

Mg^{++} 64 milligrams per liter

SO_4^{--} 1,000 milligrams per liter

$\text{CO}_3^{=}$ absent due to pH

pH 3.5

Bacterial count 50,000/100 milliliters (sulfide media, not a coliform test)

Silt density index 6.67 (Complete plugging in 2 minutes)

Turbidity 115 nephelometric turbidity unit (Total Suspended Solids 250 milligrams per liter)

Oil and grease 100 milligrams per liter

Use of these laboratory analyses with table 4-2 indicates that Rule 8 applies (see table A-2). Rule 8 states that electrodialysis reversal should be investigated. The elevated bacterial count indicates the possible contamination of the source with sewage effluent. This possible contamination should be investigated.

Assume that a bacteriological examination of a water sample indicated that the bacteria present are sulfur oxidizing bacteria, responsible for the low pH of the sample. The bacterial count may not reflect the true level of bacteria in the source, since aeration of the sample stimulates bacterial growth in the presence of the sulfide. Although no sewage effluent contamination is detected, potential taste and odor problems with this water source are severe.

Use of table 4-3 results in three possible final process selections. Rule 7, Rule 8, and Rule 9 are all applicable for this water source (see fig. A-4).

Rule 7 states that if water is below 1 nephelometric turbidity unit and has a silt density index above 4, specifications for spiral-wound reverse osmosis processes should be prepared.

Rule 8 states that if water is clear and has a silt density index of less than 4, specifications for hollow fine-fiber reverse osmosis processes should be prepared.

Rule 9 states that electrodialysis reversal specifications should be prepared. While no individual rule fits completely, Rule 9 appears to be the most applicable. As this last example demonstrates, these tables are not intended to supplant sound engineering judgment. They do not include all possible waters or conditions found in the continental United States.

Of the four water sources considered in this sample problem, the low salinity and turbidity of the 500-foot-deep well would indicate that it would be the most economical water source for development. The other three sources should be rejected. A drawing of a reverse osmosis system similar to that which would be used in treating such a well water is shown in Figure A-7.

A-2. Sample source and process selection. A facility is planned for the California coast in an area not currently served by an electric utility. Fresh surface water and groundwater do not exist or are unavailable in the area. The only water source is sea water. The facility will have 3,000 permanent personnel. Natural gas is available. Use TM 5-813-1 to determine daily water consumption. The calculation follows:

$$3,000 \text{ Persons} \times \frac{150 \text{ gallons}}{\text{day person}} \times 1.5 \text{ (Capacity Factor)}$$

Daily water consumption = 675,000 gallons per day

The area is reasonably arid with a mean summer temperature greater than 59 degrees Fahrenheit and a mean winter temperature greater than about 48 degrees Fahrenheit (see TM 5-813-1, figs. 2-5 and 2-7). Brine disposal at sea is feasible. It is estimated that electricity would cost more than \$.50/kilowatt hour if the facility could install a power transmission line. A natural gas-powered internal combustion engine could produce power for approximately \$.60/kilowatt hour.

Summarize this data as shown below:

- 1-No fresh surface water or fresh ground water are available in the area.
- 2-The site is on the Pacific Ocean and sea water is available.
- 3-Solar energy is available.
- 4-Brine disposal at sea is feasible.
- 5-Power lines are remote. A natural gas supply is available for electricity generation by internal combustion engine.

Use of table 4-1 with the above data indicates that Rule 4 will apply to a sea water source (see fig. A-8).

Source: U.S. Army Corps of Engineers

RULE	A	B	C	D	E	F
	If the freshest source of water is:	And if the desired output water will be:	And if electricity is to be generated:	And if the projected cost ratio of $\frac{264^{\circ}\text{F Steam}}{\text{Electricity}}$	Then investigate the cost of:	And have the following tests performed:
1	More salty than sea water	Potable water			Transportation of fresher water: distillation can be used but at great expense	TDS
2	Sea water	High-pressure boiler feed water	By steam turbine		Distillation followed by ion exchange	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH refer to water testing requirements in Appendix B
3	Sea water	Potable water	By steam turbine	Greater than $\frac{10 \times 10^6 \text{ BTU}}{1 \text{ kwh}}$	Thermal distillation with or without vapor compression	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH
4	Sea water	Potable water	By internal combustion engine		Vapor compression distillation and waste heat	TDS, bacterial count, turbidity
5	Sea water	Potable water	No	Less than $\frac{10 \times 10^6 \text{ BTU}}{1 \text{ kwh}}$	Reverse osmosis	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH, bacterial count, silt density index, turbidity, oil & grease refer to list for reverse osmosis, Appendix B
6	Brackish water	Potable water			Reverse osmosis	TDS, Ca^{++} , SO_4^{--} , CO_3^{--} , pH, bacterial count, silt density index, turbidity, oil & grease
7	Slightly saline brackish water	Potable water			Electrodialysis reversal	TDS, full ionic breakdown, bacterial count, turbidity refer to list for electrodialysis reversal, Appendix B

Figure A-8. Sample use of table 4-1.

Rule 4 states that when sea water is used and internal combustion engines are being considered for power production, vapor-compression distillation should be considered. Laboratory analyses of the sea water should include total dissolved solids, bacterial count, and turbidity. An evaluation of possible waste heat recovery from the power generation system should also be undertaken.

Assume the results from the laboratory analyses recommended in table 4-1, shown in figure A-9, are as follows (the format for the Physical and Chemical Analysis of Water used in this manual is for illustration purposes only and users are advised to develop their own format): The following data were extracted from the laboratory analysis and bacterial plate counts:

Seawater

TDS 35,000 milligrams per liter

Ca⁺⁺ 350 milligrams per liter as Ca⁺⁺

SO₄⁻ 2,650 milligrams per liter

pH 7.2

Bacterial count 10/100 milliliters (membrane filter technique)

Turbidity 15 nephelometric turbidity units

Assume that the following was obtained from analysis of the design of the internal combustion engine to be used for power production.

Waste heat: Approximately 1.0×10^9 British thermal units per day between 264 degrees Fahrenheit and 68 degrees Fahrenheit.

Calculating the cost of electricity from the power utility \$.50/kilowatt hour versus the cost of waste heat steam which can be produced at less than $\$0.03/1.0 \times 10^6$ British thermal units gives the following:

$\$.50/\text{kilowatt hour} / \$0.03/1.0 \times 10^6 \text{ British thermal unit} = 16.67 \times 10^6 \text{ British thermal unit per kilowatt hour}$

Use of this information and table 4-2 indicates that Rule 3 is applicable for this facility (see fig. A-10). Steam and electricity costs are compared as a ratio to eliminate dollar value changes, but technology could easily change the 10.0×10^6 British thermal unit per kilowatt hour guideline. Rule 3 states that a comparison between reverse osmosis and distillation/condensation systems should be made. Additional testing should include an alum jar test and 10-micron filter plugging, as well as evaluation of the effects of ultraviolet (UV) sterilizations.

Assume that the results from the recommended testing indicate that the turbidity can be reduced by alum addition to below 1 nephelometric turbidity unit, and a 10-micron filter will not plug rapidly on this treated water. Assume that a computer analysis in addition to figure 3-2, TM 5-813-1, shows scaling is not a problem until the total dissolved solids is concentrated about 1.5 times at temperatures below 212 degrees Fahrenheit.

Use of table 4-3 indicates that Rule 3 applies for this facility (see fig. A-11).

Rule 5 states that if temperature over 212 degrees Fahrenheit are economical for distillation at this site, acid feed may be necessary to prevent scaling.

A distillation/condensation system with an associated vapor-compression system should be evaluated. Specifications should be prepared. A drawing of a sea water distillation system capable of recompressing low-grade steam is shown in figure A-12.

A-3. Calcium sulfate solubility product (Ca SO₄ · XH₂O) scale. As can be seen below, the calculation of a solubility limit is moderately complex for a simple, pure solute at low concentration. Hand calculation is not practical in solutions containing a few percent of several cationic and/or several anionic species. Most manufacturers have computer programs that include the concentration polarization factors and any other surface-related factors that set the scaling limits for their products. The following is a sample calculation of calcium ion sulfate ion, acid-base solubility for 64 degrees Fahrenheit. To estimate solubilities for distillation condensation or other temperatures different from 64 degrees Fahrenheit, the solubility product for calcium sulfate at temperatures up to 392 degrees Fahrenheit can be found in reference (4).

These calculations are suitable for initial design and process selection (see tables 4-2 and 4-3). The principle purpose of these calculations is to indicate waters that are well below saturation and therefore do not present scaling problems. A full computer evaluation of scaling potential should be performed by the manufacturer as part of the final bid.

PHYSICAL AND CHEMICAL ANALYSIS OF WATER

1. Sample Number: Sample Problem A-2 2. Date and Hour Collected: 7-6-82
 3. From: Sea Coast, California 4:00 PM
 4. To:
 5. Sample Location and Description Sea Coast Point, Calif (Surface Sea Water)
 6. Requested By:
 7. Collected By: Joseph Blow
 8. Preservation: Reason for Request: Proposed Site for Base & DeGal. Facility

LABORATORY REPORT						
X	ITEM	UNITS	RESULTS	X	ITEM	RESULTS, mg/l
X	CO ₂ Free	mg/l	18	X	Ca	350
X	O ₂ (dissolved)	"	8	X	Mg	1300
X	H ₂ S	"	0.01	X	Na and K	11,000
X	PH	units	7.2	X	OH ^{Computed} P/mo	0
X	Temp.	*F/*C	50/10	X	HCO ₃ "	142
X	Color	units	none	X	CO ₃ "	0
X	Turbidity	NTU	15 SDI=6.66	X	SO ₄	2650
X	*P Alkalinity	mg/l	0	X	Cl	19,000
X	*MO Alkalinity	"	166	X	NO ₃	<0.1
X	*Total Hardness	"	6227	X	Fe (total)	<0.05
X	*Non-Carbonate Hardness	"	5994	X	Mn	<0.05
X	*Carbonate Hardness	"	116	X	SiO ₂	3.5
X	Total Dissolved Solids	"	34.550	X	F	1.3
X	Specific Conductance	μmhos	51,000		As	
	Others (specify as req'd)				Se	
X	Molybdenate Reactive Silicate	PPM	2.0		Pb	
X	Molybdenate non-Reactive Silicate	PPM	0.5		B	
X	Bromide (Br)	PPM	65		Cu	
X	10 mg/L Oil	PPM	<1.0		Zn	
					Cr (+6)	
					Cd	
	*As CaCO ₃				CN	

X Indicate if required

- (1) 10 Minute Demand.
- (2) Utilize a 50 fold, low temperature, low pressure concentrating technique to verify <10 mg/l Oil & Grease.
- (3) A Silt Density Index determination must be made on all waters with a turbidity of less than 2 NTU.

Figure A-9. Water analysis (sample problem A-2).

RULE	A	B	C	D	E	F
	If the feed water TDS is (mg/liter):	And if the raw feed water suspended solids are:	And if the product of the $[Ca^{++}] [SO_4^{--}]$ moles ² /liter ² is in the reject brine (see sample problem A-3)	And if the oil and grease in the raw feed water is:	Then investigate the cost of:	And have the following pretreatment processes investigated for effectiveness:
1	Greater than 50,000				Transportation of fresher water; distillation of this water is extremely expensive	Precipitation of less soluble salts
2	Between 20,000 - 50,000	Over 20 NTU	Considerably less than 2×10^{-4}	Greater than 10 mg/liter	Reverse osmosis or distillation and steam and electricity	Alum jar tests, pH adjustment 10-micron or smaller filter plugging
3	Between 20,000 - 50,000	Over 1 NTU		Less than 10 mg/liter	Reverse osmosis	Alum jar tests 10-micron or smaller filter plugging UV sterilization
4	Between 20,000 - 50,000	Less than 1 NTU SDI greater than 3		Less than 10 mg/liter	Spiral-wound membrane reverse osmosis	pH adjustment, UV sterilization, chlorine disinfection, chlorine residual
5	Between 20,000 - 50,000	SDI under 3		Less than 10 mg/liter	Hollow fine-fiber membrane reverse osmosis	10-micron or smaller filter test, UV sterilization
6	Between 3,000 - 20,000	Over 1,000 mg/liter	Considerably less than 2×10^{-4}	Greater than 10 mg/liter	Distillation	pH adjustment, alum jar test
7	Between 3,000 - 20,000			Less than 10 mg/liter	Reverse osmosis	pH adjustment, alum jar test, silt density index, UV sterilization
8	Between 500 - 4,000				Electrodialysis reversal	pH adjustment, alum jar test, 10-micron filter plugging, chlorine disinfection

†Note: Only 500 mg/liter potable water is considered after table 4-1.

Figure A-10. Sample use of table 4-2.

Source: U.S. Army Corps of Engineers

R C E	A	B	C	D	E	F	G
	If the treated feed water salinity (mg/l) will be (see note):	And the cost ratio of 264°F steam 1 kwh electricity will be:	Alkaline earths on the raw water are such that (see sample problem A-3):	And the treated suspended solids are:	And the designated chlorine residual is:	Then investigate the cost of:	With the following pre- and post-treatment technique costs:
1	Between 20,000 - 50,000		Within 66% of saturation	Less than 1 NTU but SDI greater than 3	0.0 mg/liter	Spiral-wound membrane reverse osmosis	Whatever treatment is necessary to produce D and E
2	Between 20,000 - 50,000		Within 66% of saturation	SDI less than 3	0.0 mg/liter	Hollow fine-fiber membrane reverse osmosis	Whatever treatment is necessary to produce D and E
3	Between 20,000 - 50,000			Less than 1 NTU	Between 1.0 and 0.0 mg/l	Chlorine-resistant membrane reverse osmosis	Whatever treatment is necessary to produce D and E
4	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh	Within 50% of saturation	Greater than 1 NTU	More than 1 mg/l	Some form of distillation under 185° F	Anti-scalent
5	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh		Greater than 1 NTU	More than 1 mg/l	Some form of distillation	Acid feed (hydrochloric is best)
6	Between 20,000 - 50,000	Greater than 10×10^6 BTU 1 kwh	$[Ca^{++}]$ multiplied by $[SO_4^{--}]$ Well Under 2×10^{-6}	Greater than 1 NTU	More than 1 mg/l	Some form of distillation	No pretreatment for calcium sulfate scale control
7	Between 3,000 - 20,000			Less than 1 NTU but SDI greater than 3	Less than 1.0 mg/l**	Brackish water spiral-wound membrane reverse osmosis	Whatever treatment is necessary to produce D and E
8	Between 3,000 - 20,000			SDI less than 3	Less than 1.0 mg/l**	Brackish water hollow fine-fiber membrane reverse osmosis	Whatever treatment is necessary to produce D and E
9	Between 500 - 4,000 and especially when expected to vary by more than 15%			Will not plug 10-micron filter	0.0 mg/l**	Electrodialysis reversal	Turbidity removal To 1 NTU and disinfection to less than 1/100 ml.
10	Is stable at some value between 500 - 1000			SDI less than 3	Less than 1.0 mg/l**	Low pressure/high flux membrane reverse osmosis	Whatever treatment is necessary to produce D and E

*Note: Only 500 mg/l of potable water is considered after table 4-1

Desalination of water more saline than 50,000 mg/liter is not considered after table 4-2.

**For chlorine-resistant membranes only, and for polyaromatic amide membranes, 0.0 mg/l.

Figure A-11. Sample use of table 4-3.

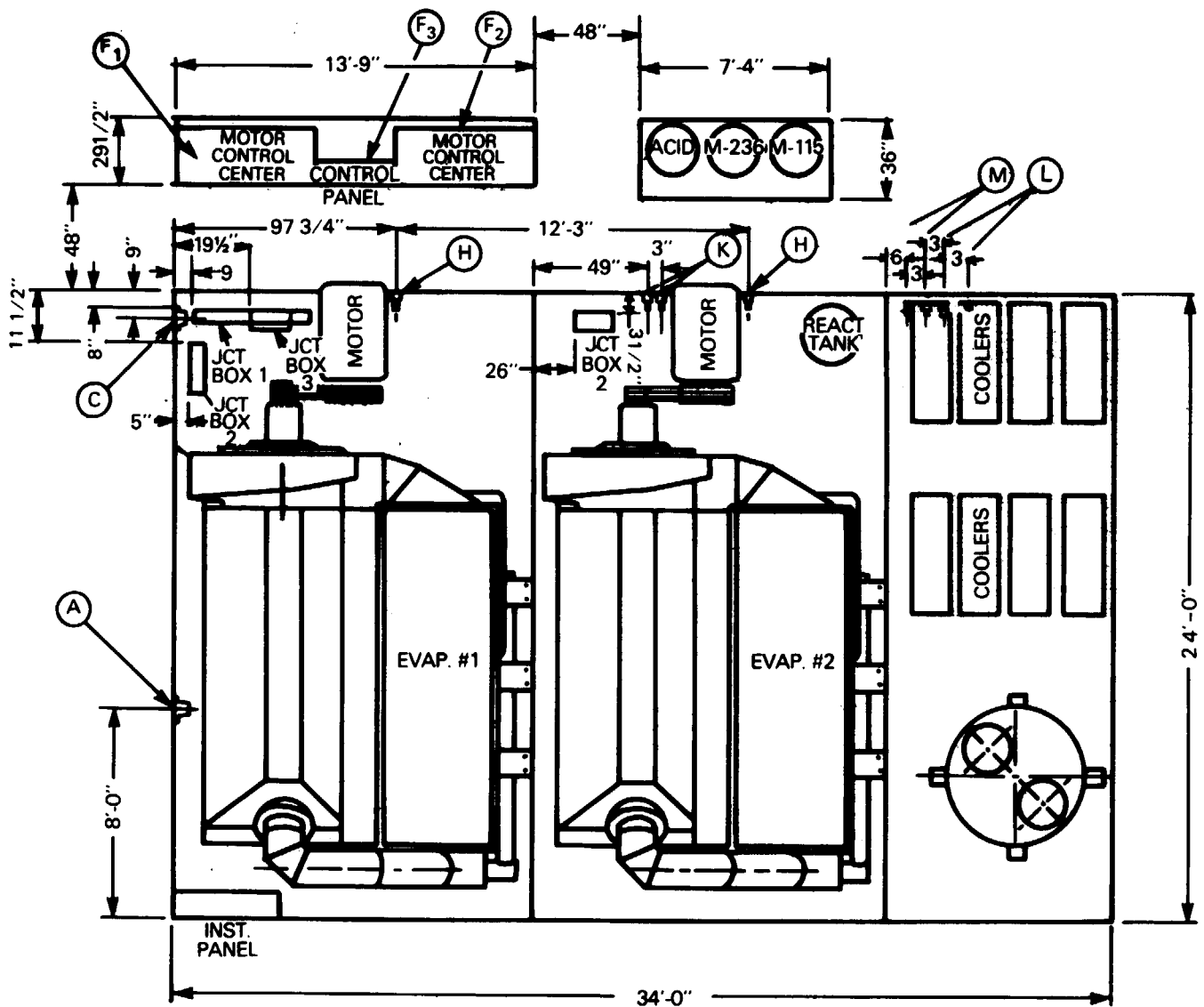


Figure A-12. Plan view of a vapor compression system.

Symbols:

$[Ca^{++}]$	=	Double-ionized calcium concentration in moles/liter (molar)
$[SO_4^{--}]$	=	Double-ionized sulfate concentration in moles/liter (molar)
$[HSO_4^-]$	=	Undissociated bisulfate ion concentration in moles/liter (molar)
$[H^+]$	=	The dissociated hydrogen ion concentration in moles/liter (molar)
pK_{sp}	=	The negative base 10 logarithm of the solubility product
K_{sp}	=	The product of the concentration of the ions in a saturated solution that is beginning to form crystals
pH	=	The negative base 10 logarithm of the hydrogen ion concentration
pOH	=	The negative base 10 logarithm of the hydroxyl ion concentration
pK_a	=	The negative base 10 logarithm of the acid dissociation constant
K_a	=	The ratio of the concentration of dissociated acid and hydrogen ion concentration to the undissociated acid concentration at equilibrium

Assume that:

The water contains 1,000 parts per million as CaCO_3 , 2,650 parts per million $\text{SO}_4^{=}$ as total sulfate and is at $\text{pOH} = 11$. Assume that the temperature is close to 64 degrees Fahrenheit and that there is no ion pairing of SO_4 other than hydrogen ion as HSO_4 .

The pK_{sp} of calcium sulfate is given as 3.6.

The pK_a of sulfuric acid second dissociation is given as 1.92.

The density of the saline water sample is 1,025 grams/liter at 64 degrees Fahrenheit.

To convert calcium and sulfate concentrations in the expected brine (density = 1025 grams/liter) to molarity use the following calculations:

$$\begin{aligned}\text{Molar Concentration} &= \frac{1 \text{ gram Ca}^{++} \text{ as CaCO}_3}{1000 \text{ grams H}_2\text{O}} \times \frac{1025 \text{ grams}}{1 \text{ liter}} \times \frac{1 \text{ mole Ca}^{++}}{100 \text{ grams CaCO}_3^{**}} \\ &= 0.01025 \text{ molar}\end{aligned}$$

$$\begin{aligned}\text{Molar Concentration of SO}_4 &= \frac{2650 \text{ milligrams SO}_4^{=} \text{ as total SO}_4^{=}}{1000 \text{ grams H}_2\text{O}} = \frac{1025 \text{ grams}}{\text{liter}} \times \frac{1 \text{ mole SO}_4^{=}}{96,063 \text{ milligrams SO}_4^{=*}} \\ &= 0.0283 \text{ molar [SO}_4^{=}\end{aligned}$$

$$\text{Molar concentration of sulfate} = 0.0283 \text{ molar [SO}_4^{=}]$$

*molecular weight $\text{SO}_4^{=}$ in milligram/mole

**molecular weight CaCO_3

$$-\log_{10} ([\text{Ca}^{++}][\text{SO}_4^{=}]) = \text{pK}_{\text{sp}} = 3.6$$

$$\therefore K_{\text{sp}} = ([\text{Ca}^{++}][\text{SO}_4^{=}]) = 2.51 \times 10^{-4}$$

$$\text{pH} + \text{pOH} = 14$$

$$\text{pOH} = 11 \quad \therefore \text{pH} = 3$$

$$\text{pH} = -\log [\text{H}^+] \quad \therefore [\text{H}^+] = 10^{-3} \text{ moles/liter}$$

$$-\log_{10} ([\text{H}^+][\text{SO}_4^{=}]/[\text{HSO}_4^{-}]) = \text{pK}_a = 1.92$$

$$\therefore K_a = 1.20 \times 10^{-2} = [\text{H}^+][\text{SO}_4^{=}]/[\text{HSO}_4^{-}]$$

\therefore for this water, which is at $\text{pOH} = 11$

$$[\text{SO}_4^{=}]/[\text{HSO}_4^{-}] = 1.2 \times 10^{-2}/10^{-3} = 12 \quad \therefore \text{of the total sulfate}$$

$$\frac{12}{[12 + 1]} = \frac{12}{13} \text{ is } [\text{SO}_4^{=}] \quad \therefore [\text{SO}_4^{=}] = .92 [\text{Total SO}_4^{=}]$$

$$(\text{for pH } 1 [\text{SO}_4^{=}] = 0.107 [\text{Total SO}_4^{=}])$$

Since only 92 percent of this total $\text{SO}_4^{=}$ is in solution as $\text{SO}_4^{=}$ and 8 percent is as HSO_4^{-} at pH 3, the following equation is applicable:

$$\begin{aligned}[\text{Ca}^{++}] \times \frac{\text{percent as SO}_4^{=}}{100} \times [\text{SO}_4^{=}] &= (.01025)(.0283) \frac{92}{100} \\ &= 2.67 \times 10^{-4}\end{aligned}$$

$$2.67 \times 10^{-4} \text{ is greater than } K_{\text{sp}} = 2.51 \times 10^{-4}$$

\therefore Unless other ions complex Ca^{++} or SO_4 , scaling will be a problem at 64 degrees Fahrenheit. (See figure 5-2.)

A-4. Ion- exchange desalination. A permanent installation is proposed near Haftrak, Arizona. The potable water treatment system will serve a resident population of 2,000. Use TM 5-813-1 to obtain water consumption per day. The calculation is as follows:

$$\begin{aligned}&\frac{150 \text{ gallons}}{2,000 \text{ persons} \times \text{day Person} \times 1.5 \text{ capacity factor}} = 450,000 \text{ gallons per day}\end{aligned}$$

The area is hot and dry, with annual average maximum daily air temperature of 55 degrees Fahrenheit and a net pan evaporation of approximately 87 inches. Ground water is available, as well as an average chemical analysis.

PHYSICAL AND CHEMICAL ANALYSIS OF WATER

1. Sample Number: Sample Problem A-4 2. Date and Hour Collected: 07-13-82
 3. From: HAFTRAK, A2 10:00 PM
 4. To:
 5. Sample Location and Description Well A-2-4 Groundwater
 6. Requested By:
 7. Collected By: MISS BUZLEY
 8. Preservation: Reason for Request: Water Quality Survey

LABORATORY REPORT						
X	ITEM	UNITS	RESULTS	X	ITEM	RESULTS, mg/l
	CO ₂	mg/l	0		Ca	20
	O ₂ (dissolved)	"			Mg	3
	H ₂ S	"			Na and K	225
	PH	units	8.5		OH	0
	Temp .	*F/*C	58/14.4		HCO ₃	32+
	Color	units			CO ₃	25
	Turbidity	NTU			SO ₄	77
	*P Alkalinity	mg/l	21		Cl	107
	*MO Alkalinity	"	300		NO ₃	9
	*Total Hardness	"	62		Fe (total)	<0.01
	*Non-Carbonate Hardness	"	0		Mn	<0.01
	*Carbonate Hardness	"	62		SiO ₂	5
	Total Dissolved Solids	"	800		F	2.0
	Specific Conductance	μmhos			As	
	Others (specify as req'd)				Se	
					Pb	
					B	
					Cu	
					Zn	
					Cr (+6)	
					Cd	
	*As CaCO ₃				CN	

X Indicate if required

Figure A-13. Water analysis (sample problem A-4).

The assumed site data are summarized below:

- 1-Available ground water is a consideration.
- 2-Ion exchange will be considered for the potable water treatment.
- 3-Pond evaporation of regenerate wastes would be approximately 0.7, multiplied by net pan evaporation (87 inches per year), which equals 508 inches per year.

Ground Water

Laboratory analyses are available, and the following water quality data are shown in figure A-13.

Ion-Exchange Resin Selection

On the physical and chemical analysis of water report (fig. A-13), the following data were extracted:

Total dissolved solids	800 milligrams per liter
Sulfate	77 milligrams per liter
Chloride	107 milligrams per liter
Nitrate	9 milligrams per liter
Iron	0.01 milligrams per liter
Manganese	0.01 milligrams per liter
Fluoride	2.0 milligrams per liter

In comparing the extracted data with the potable water maximum contaminant levels found in Army Medical Corps documents, total dissolved solids is the only limit exceeded.

The choice of the proper ion-exchange method depends on the composition of the raw water and its intended use. A strongly acidic cation exchange resin replaces the cations in the raw water with hydrogen, and the effluent from the exchanger unit is both softened and acidic. Since sodium is the most predominant cationic ion in the well water, a reduction of sodium and associated alkalinity will reduce the total dissolved solids to within the potable water limits. Therefore, a strongly acidic cation exchange resin system is indicated. No specific pretreatment process is necessary.

Neutralization

A strongly acidic cation exchange system converts carbonate and bicarbonate alkalinity to carbonic acid, which breaks down to carbon dioxide and water. Then, the carbon dioxide may be removed by air stripping in a degasification tower. After degasification, a percentage of the raw well water containing alkalinity may be blended to obtain the desired 500 milligrams per liter of total dissolved solids.

Ion-Exchange Engineering Data

Since total dissolved solids only need to be reduced approximately 40 percent, consider low acid regeneration levels. Regeneration levels of 5 and 3 pounds per cubic foot will be considered. Leakage can be estimated from vendor data such as figure A-14.

With a 5-pound H_2SO_4 (66 degrees Be)/cubic foot regeneration level, the average sodium leakage equals 60.5 parts per million as CaCO_3 . The capacity of the ion-exchange resin can be found in figure A-15.

With a 5-pound H_2SO_4 (66 degrees Be)/cubic foot regeneration level, the book capacity = 15.1 kilograins/cubic foot. The alkalinity correction factor can be found in figure A-16.

At 56 percent, the alkalinity correction factor is 1.125

The corrected capacity = 17.0 kilograins/cubic foot.

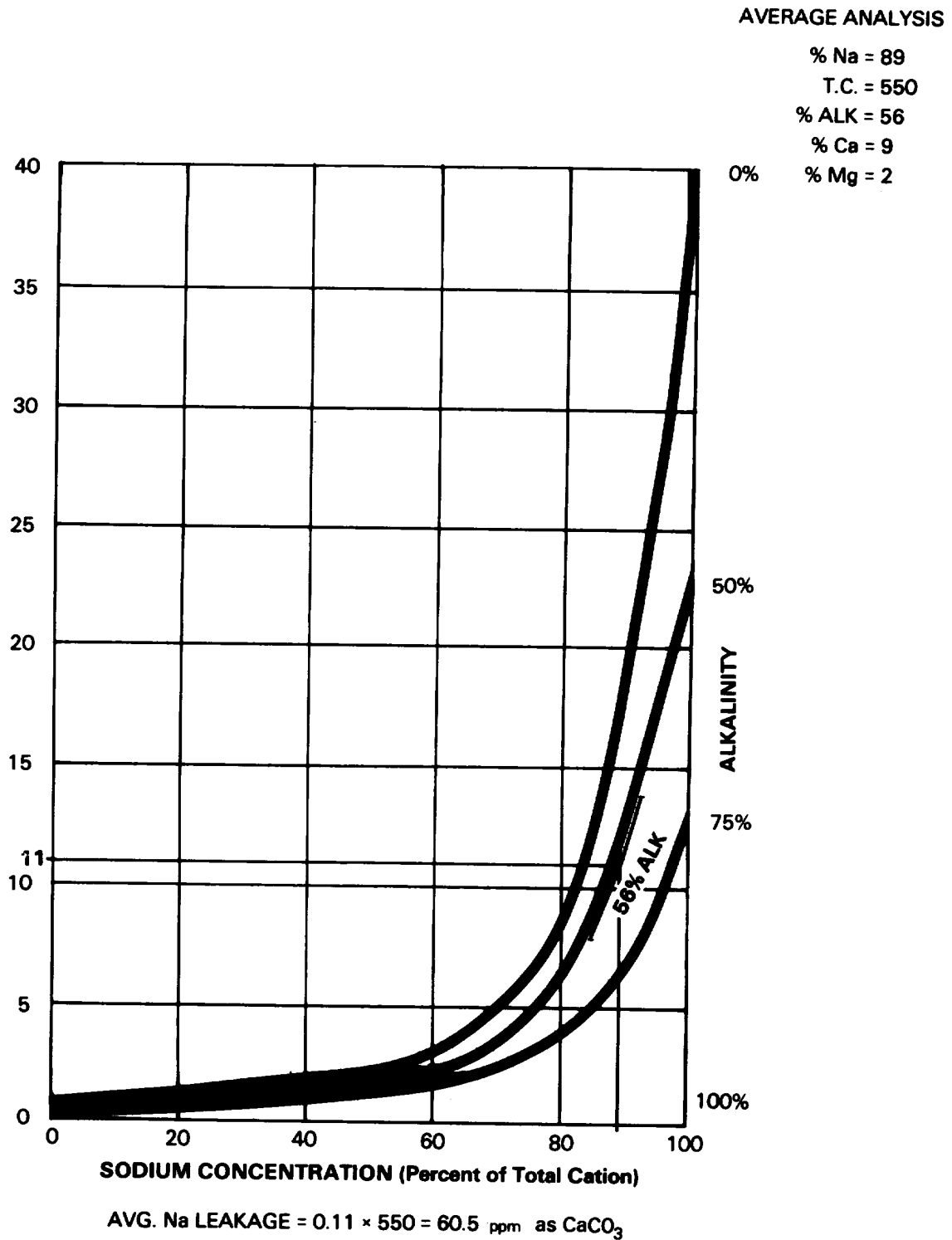
Then

Use equipment factor = 0.8

\therefore Design Capacity = 13.6 kilograins/cubic foot.

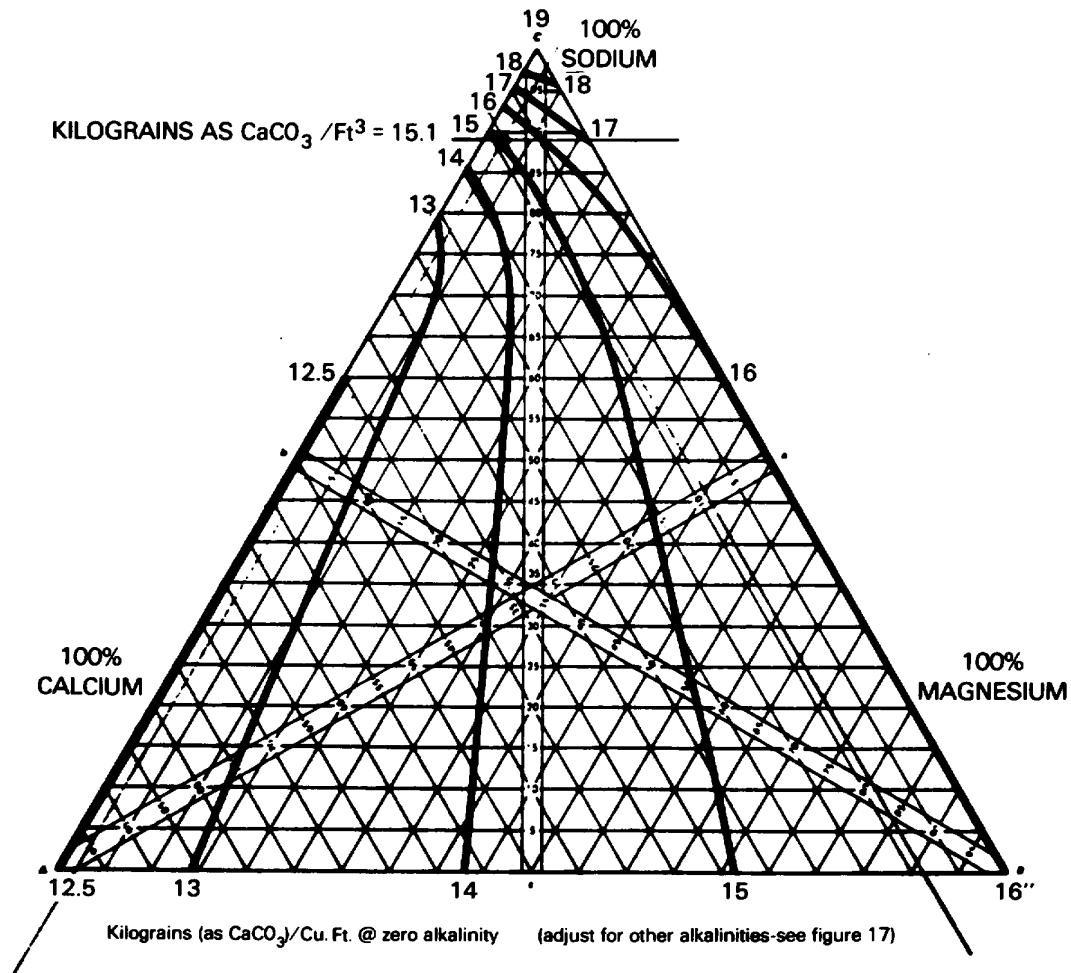
With a 3-pound H_2SO_4 (66 degrees Be)/cubic foot regeneration level, the average sodium leakage = 104.5 parts per million as CaCO_3 . Leakage can be estimated from vendor data such as figure A-17.

With a 3-pound H_2SO_4 (66 degrees Be)/cubic foot regeneration level, the book capacity = 11.0 kilograins/cubic foot. The capacity of the ion-exchange resin can be found in figure A-18.



Source: Rohm and Haas Co.

Figure A-14. Amberlite IR-120 plus leakage data regeneration-5 lbs. H_2SO_4 (66° Be)/cu. ft.

BOOK CAPACITY = 15.1 KGR/Ft³

Source Rohm and Haas Co

Figure A-15. Amberlite IR-120 plus iso-capacity data regeneration-5 lbs. H_2SO_4 (66° Be)/cu. ft.

With a 5-pound H_2SO_4 (66 degrees Be)/cubic foot regeneration level, the book capacity = 15.1 kilograins/cubic foot. The alkalinity correction factor can be found in figure A-19.

Then

The corrected capacity = 12.4 kilograins/cubic foot.

Then

Use equipment factor = 0.8.

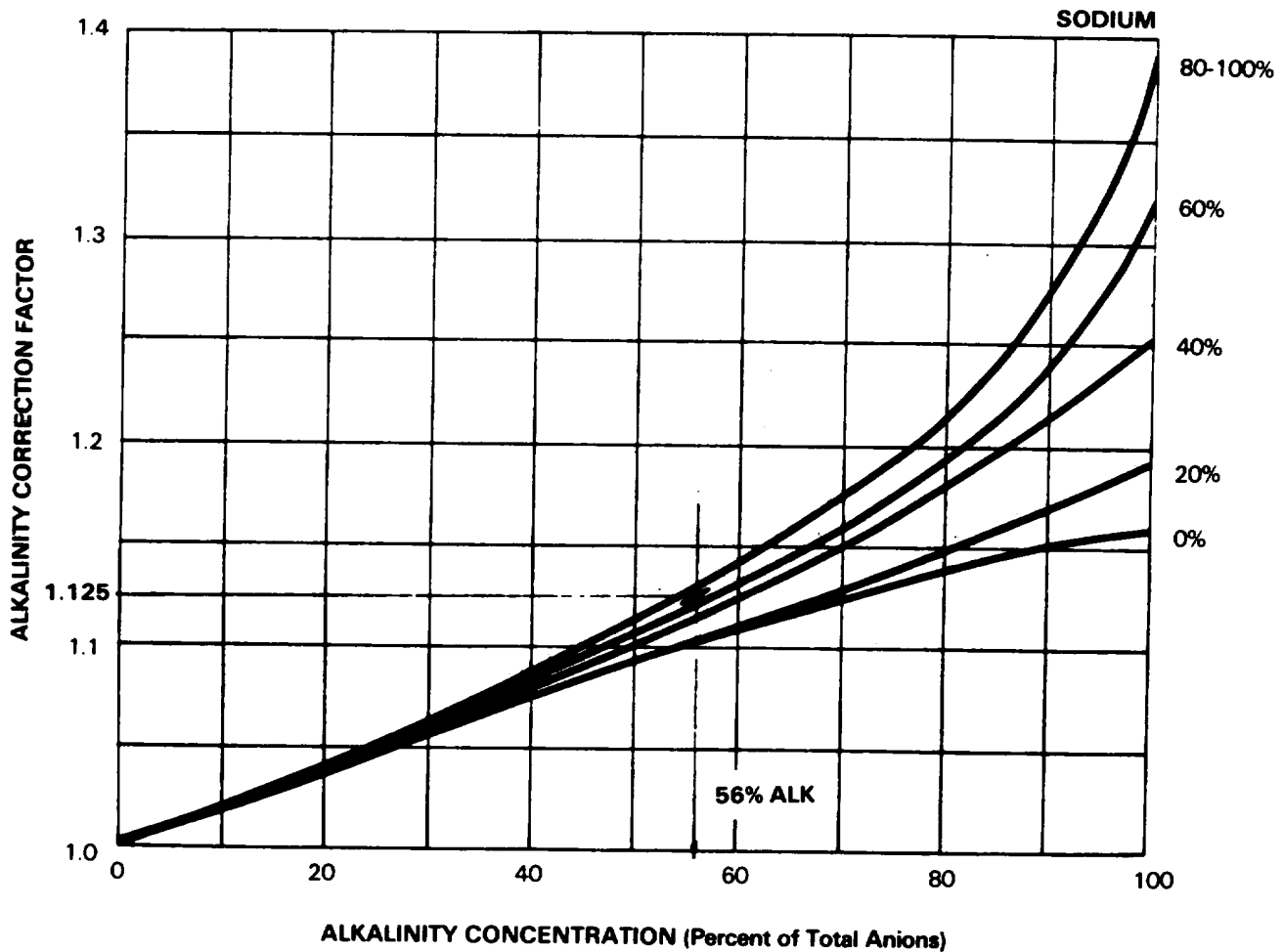
∴ Design Capacity = 9.9 kilograins/cubic foot.

Water Analyses Summary

Table A-1 is a summary of the average water constituents at different stages in the ion-exchange treatment process.

$$@ 56\% \text{ ALK} = 15.1 \times 1.125 = 17.0 \text{ KGR/Ft}^3$$

USE 0.8 EQUIPMENT FACTOR
 $17.0 \times 0.8 = 13.6 \text{ KGR/Ft}^3$
 DESIGN CAPACITY



Source: Rohm and Haas Co.

Figure A-16. Amberlite IR-120 plus capacity correction for alkalinity.

When using 5-pound H_2SO_4 (66 degrees Be) per cubic foot regeneration, the cation exchanger effluent will have approximately zero calcium and magnesium, with a sodium leakage of 61 parts per million as indicated on Figure A-14. The remaining cations are hydrogen as indicated.

The anions are not affected, with the exception of alkalinity, which is converted to carbon dioxide and water.

The next step in the treatment is blending sufficient raw water to neutralize the hydrogen ions in the cation effluent.

AVERAGE ANALYSIS

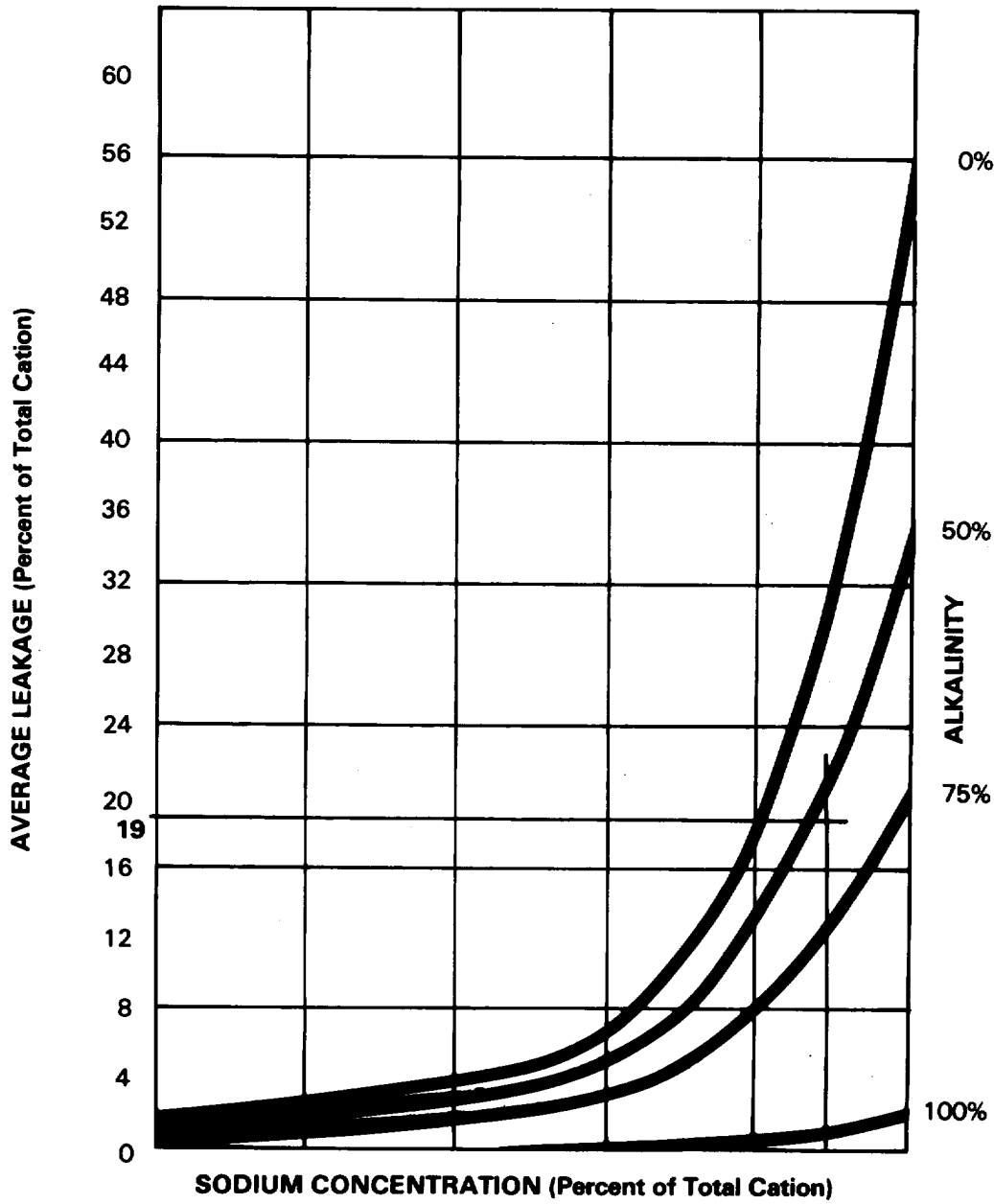
% Na = 89

T.C. = 550

% ALK = 56

% Ca = 9

% Mg = 2



$$\text{AVG. Na LEAKAGE} = 0.19 \times 550 = 104.5 \text{ PPM as CaCO}_3$$

Source: Rohm and Haas Co.

Figure A-17. Amberlite IR-120 plus leakage data regeneration-3 lbs. H_2SO_4 (66° Be)/cu. ft.

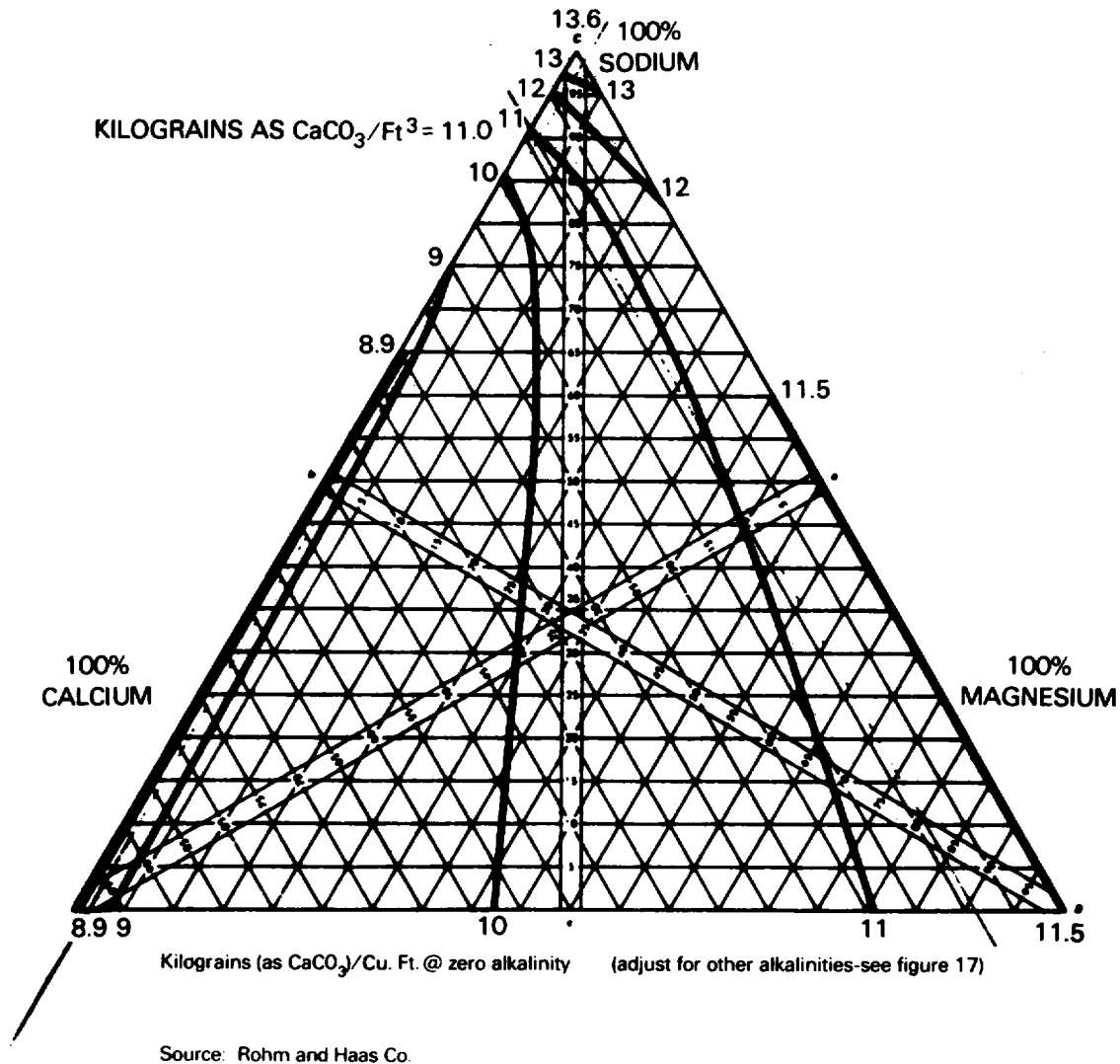
BOOK CAPACITY = 11.0 KGR/Ft³

Figure A-18. Amberlite IR-120 plus iso-capacity data regeneration-3 lbs. H_2SO_4 (66° Be)/cu. ft.

Neutralized Blend (N.B.)

$$\frac{181 \text{ parts per million hydrogen as } CaCO_3}{308 \text{ parts per million alkalinity as } CaCO_3} = 0.59 \text{ Volume Ratio}$$

Or
Per unit volume of cation effluent, 0.59 volume of raw water is required to neutralize the hydrogen ions.

$$\frac{0.59}{1.59} = .37 \times 100 = 37 \text{ percent of neutralized blend is raw water}$$

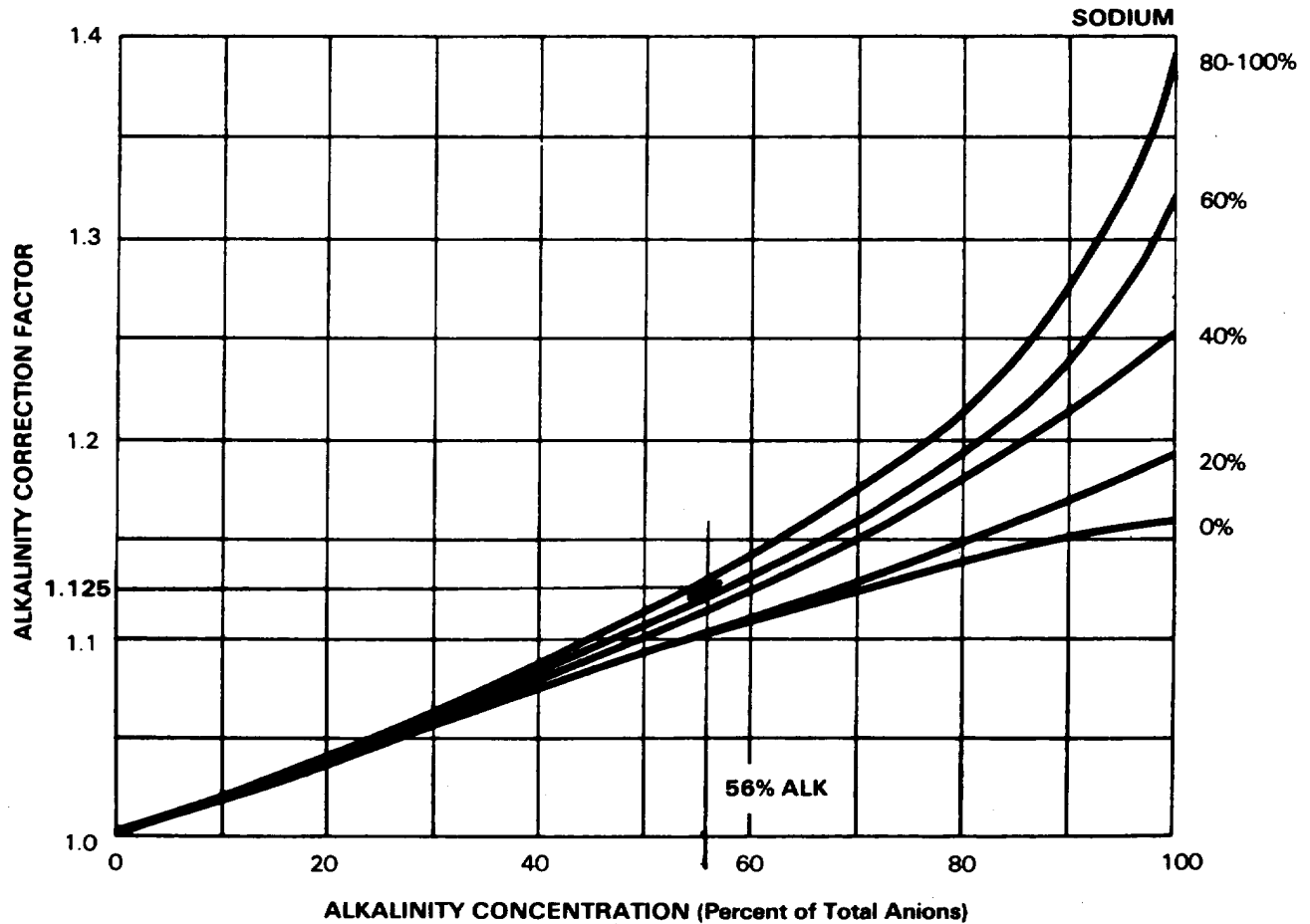
Raw Water = R.W.
Neutral Blend = N.B.
Potable = P

$$@ 56\% \text{ ALK} = 11.0 \times 1.125 = 12.4 \text{ KGR/Ft}^3$$

USE 0.8 EQUIPMENT FACTOR

$$12.4 \times 0.8 = 9.9 \text{ KGR/Ft}^3$$

DESIGN CAPACITY



Source: Rohm and Haas Co.

Figure A-19. Amberlite IR-120 plus capacity correction for alkalinity.

100x = percent of R.W. in P
P - N.B.

$$x = \frac{\text{P} - \text{N.B.}}{\text{R.W.} - \text{N.B.}}$$

$$= \frac{500 - 303}{800 - 303} = \frac{197}{497} = 0.396$$

$$100x = 0.396$$

x = 39.6 percent R.W. in P.

$$100x(1 - .396) = 60.4 \text{ percent N.B. in P.}$$

The blended potable water has a Langelier Index of + 0.65, which produces a slight scaling tendency for distribution system corrosion protection.

	Raw		Cation Effluent		(Degased) Neutralized Blend		500 Total Dissolved Solids	
	Ion	CaCO ₃	Ion	CaCO ₃	Ion	CaCO ₃	Ion	CaCO ₃
Ca	20	50	0	0	7.5	18.5	12	31
Mg	3	12	0	0	1	4.5	2	7.5
Na	225	488	28	61	101	219	150	325.5
H				181				
Total Cations		550		242		242		364
HCO ₃	324	266	0	0	0	0	141	116
CO ₃	25	42	0	0	0	0	4	6
SO ₄	77	80	77	80	77	80	77	80
Cl	107	151	107	151	107	151	107	151
NO ₃	9	11	9	11	9	11	9	11
Total Anions		550		242		242		364
pH	8.5						9.0	
Total Dissolved Solids	800				303		502	
*CO ₂ by Design					* 10	* 11	0	0
CO ₂ EQ. WT. = 44								

500 TOTAL DISSOLVED SOLIDS WATER

$$\begin{aligned}
 \text{Ca} &= (50 \times .396) + (18.5 \times .604) = 30.9 \\
 \text{Mg} &= (12 \times .396) + (4.5 \times .604) = 7.47 \\
 \text{Na} &= (488 \times .396) + (219 \times .604) = 325.52 \\
 \text{HCO}_3 &= (266 \times .396) + \quad = 105 \quad + 11 \text{ parts per million CO}_2 \text{ as CaCO}_3 = 116 \\
 \text{CO}_3 &= (42 \times .396) \quad = 16.6 - 11 \text{ parts per million CO}_2 \text{ as CaCO}_3 = 5.6
 \end{aligned}$$

Langelier Index = +0.65

Table A-1. Water Constituents at Treatment Stages with 5 Pounds/Cubic Foot Acid Regeneration.

	Raw		Cation Effluent		(Degased) Neutralized Blend		500 Total Dissolved Solids	
	Ion	CaCO ₃	Ion	CaCO ₃	Ion	CaCO ₃	Ion	CaCO ₃
Ca	20	50	0	0	6	16	12	30
Mg	3	12	0	0	1	4	2	7
Na	225	488	48	104.5	102	222	151	328
H				137.5				
Totals Cations		550		242				
HCO ₃	324	266	0	0	0	0	143	117
CO ₃	25	42	0	0	0	0	4	6
SO ₄	77	80	77	80	77	80	77	80
Cl	107	151	107	151	107	151	107	151
NO ₃	9	11	9	11	9	11	9	11
Total Anions		550		242				
pH	8.5						8.9	
Total Dissolved Solids	800				302		505	
*CO ₂ by Design					* 10	* 11		
CO ₂ EQ. WT. = 44								

500 TOTAL DISSOLVED SOLIDS WATER

$$\begin{aligned} \text{Ca} &= (50 \times .398) + (16 \times .602) = 29.53 \\ \text{Mg} &= (12 \times .398) + (4 \times .602) = 7.18 \\ \text{Na} &= (488 \times .398) + (222 \times .602) = 327.87 \\ \text{HCO}_3 &= (266 \times .398) + 11 \text{ parts per million CO}_2 \text{ as CaCO}_3 = 116.87 \\ \text{CO}_3 &= (42 \times .398) - 11 \text{ parts per million CO}_2 \text{ as CaCO}_3 = 5.72 \end{aligned}$$

Langelier Index = +0.54

Table A-2. Water Constitutes at Treatment Stages with 3 Pounds/Cubic Foot Sulfuric Acid Regeneration

Source U S Army Corps of Engineers

Table A-2 is a summary of the average constituents at different stages in the ion-exchange treatment process.

When using 3-pounds H₂SO₄ (66 degrees Be) per cubic foot regeneration, the cation exchange effluent will have approximately zero calcium and magnesium, with a sodium leakage of 104.5 parts

per million as indicated on figure A-17. The remaining cations are hydrogen as indicated.

After degasification of the neutral blend, the carbon dioxide is 10 parts per million based on the degasifier design. Raw water is again blended after degasification to achieve a 500 milligram per liter of total dissolved solids product.

Neutralized Blend (N.B.)

137.5 parts per million hydrogen as CaCO_3 0.45 volume ratio

308 parts per million alkalinity as CaCO_3

Or

0.45 Volume

1.45 Volume = $0.32 \times 100 = 32$ percent of neutralized blend is raw water

Two-step blending is considered to take advantage of the carbonate in the raw water, which will neutralize the remaining carbon dioxide and reduce potential corrosion in the distribution system.

Blend of Well Water and Neutral Degased Water

R.W. = 800 milligrams per liter of Total Dissolved Solids

N.B. = 302 milligrams per liter of Total Dissolved Solids

P = 500 milligrams per liter of Total Dissolved Solids

$100x =$ Percent of R.W. in P

$$= \frac{P - \text{N.B.}}{\text{R.W.} - \text{N.B.}}$$

$$x = \frac{500 - 302}{800 - 302} = 0.398$$

$$100x = 0.398$$

$$x = 39.8 \text{ R.W. in P}$$

$$100x (1 - .398) = 60.2 \text{ percent of N.B. in P}$$

The blended potable water has a Langelier Index of +0.54, which indicates a slight scaling tendency for the distribution system corrosion protection.

Chemical Requirements

3 pounds/cubic foot regeneration level

\therefore In 1,000 gallons of potable water

398 gallons of raw water to 500 total milligrams per liter of dissolved solids

+ $(1,000 - 398) \times .32 = 193$ gallons to neutralize

Or

$398 + 193 = 591$ gallons of raw water and 409 gallons of cation effluent

So

40.9 percent of potable water is treated with the cation exchanger.

Acid Usage

Cation Regeneration Efficiency

$$\frac{50 \text{ grains } \text{CaCO}_3 \times (3 \text{ pounds/cubic feet}) (.93 \text{ pounds acid/pounds}) (7 \text{ kilograins/pounds})}{49 \text{ grains } \text{H}_2\text{SO}_4} = 2.01$$

9.9 kilograins/cubic feet
or 200-percent stoichiometric

Cations Removed Per Gallons of Potable Water

$$\begin{aligned} & \frac{(409 \text{ gallons})}{\text{kilogallon}} \times \frac{488 \text{ parts per million} - 104.5 \text{ parts per million}}{17.1 \text{ parts per million/grains/gallon}} \times \frac{1 \text{ pound}}{7000 \text{ grains}} \\ &= \frac{1.31 \text{ pounds as CaCO}_3}{1000 \text{ gallons potable water}} \end{aligned}$$

At 200-percent regeneration efficiency:

$$\begin{aligned} \text{Acid Required} &= 2.0 \times \frac{1.31 \text{ pounds as CaCO}_3}{\text{kilogallons potable water}} \times \frac{49 \text{ equivalent weight acid}}{50 \text{ equivalent weight CaCO}_3} \\ &\times \frac{1 \text{ pound H}_2\text{SO}_4}{.995 \text{ percent H}_2\text{SO}_4} \\ &= 2.58 \text{ pounds 99.5 percent H}_2\text{SO}_4 \text{ per 1000 gallons potable water} \end{aligned}$$

Waste Acid

$$(2.0 - 1.0) \frac{1.29 \text{ pounds acid}}{\text{kilogallons potable water}} \times 1.29 \frac{\text{pounds 99.5 percent H}_2\text{SO}_4}{1000 \text{ gallons potable water}}$$

Chemical Costs

Acid Cost = 3 cents/pound 99.5 percent H₂SO₄

NaOH Cost = 10 cents/pound 100 percent NaOH

Regeneration Acid = 1.29 pounds 99.5 percent H₂SO₄

If neutralization of the waste acid is required prior to disposal:

$$\text{Waste Acid} = \frac{1.29 \text{ pounds 99.5 percent H}_2\text{SO}_4}{1000 \text{ gallons potable water}}$$

If we use 100 percent NaOH

$$\text{NaOH} = 1.32 \text{ pounds of 100\% acid as CaCO}_3 \times \frac{40 \text{ equivalent weight NaOH}}{50 \text{ equivalent weight CaCO}_3}$$

$$= \frac{1.05 \text{ pounds of 100 percent NaOH}}{1000 \text{ gallons potable water}}$$

Summary of Cost Per 1000 Gallons of Potable Water

Cation exchange acid usage = 1.29 pounds x 3.0 cents = 3.87 cents

Waste acid = 1.29 pounds x 3.0 cents = 3.87 cents

Neutralization NaOH = 1.05 pounds x 10 cents = 10.5 cents

5 Pounds/Cubic Foot Regeneration Level

∴ In 1000 gallons potable water

396 gallons raw water to 500 milligrams per liter of total dissolved solids + (1000 - 396) x .37 = 223.5 gallons to neutralization

Or

$$396 + 223.5 = 619.5 \text{ gallons of raw water}$$

And

$$380.5 \text{ gallons of cation effluent}$$

So:

38 percent of potable water is treated with the cation exchanger

Acid Usage

Cation Regeneration Efficiency

$$\frac{50 \text{ Equivalent Weight CaCO}_3}{49 \text{ Equivalent Weight H}_2\text{SO}_4} \times \frac{(5 \text{ pounds/cubic feet}) (.93 \text{ pounds acid/pound}) (7 \text{ kilograins/pound})}{13.6 \text{ kilograins/cubic feet}} = 2.44$$

or 250 percent stoichiometric

Cations Removed

$$\begin{aligned} & \frac{380.5 \text{ gallons}}{\text{kilogallon potable water}} \times \frac{488 \text{ parts per million} - 61 \text{ parts per million}}{17.1 \text{ parts per million/grains/gallon}} \times \frac{1 \text{ pound}}{7000 \text{ grains}} \\ &= \frac{1.36 \text{ pounds as CaCO}_3}{1000 \text{ gallons potable water}} \end{aligned}$$

At 250 Percent Regeneration Efficiency:

Acid Required

$$\begin{aligned} &= 2.5 \frac{1.36 \text{ pounds as CaCO}_3}{1 \text{ kilogallon potable water}} \times \frac{49 \text{ equivalent weight acid}}{50 \text{ equivalent weight CaCO}_3} \times \frac{1 \text{ pound H}_2\text{SO}_4}{.995 \text{ percent H}_2\text{SO}_4} \\ &= 3.35 \frac{\text{pounds 99.5 percent H}_2\text{SO}_4}{1000 \text{ gallons potable water}} \end{aligned}$$

Waste Acid

$$(2.5 - 1.0) \times 1.34 = 2.01 \text{ pounds acid/1000 gallons potable water}$$

Chemical Costs

Acid Cost = 3 cents/pound 99.5 percent H₂SO₄

NaOH Cost = 10 cents/pound 100 percent NaOH

$$\text{Regeneration Acid} = \frac{1.34 \text{ pounds 99.5 percent H}_2\text{SO}_4}{1000 \text{ gallons potable water}}$$

If neutralization of the waste acid is required prior to disposal:

$$\text{Waste acid} = \frac{2.01 \text{ pounds 99.5 percent H}_2\text{SO}_4}{1000 \text{ gallons potable water}}$$

If we use 100 percent NaOH

$$\begin{aligned} \text{NaOH} &= 2.04 \text{ pounds of 100\% acid as CaCO}_3 \times \frac{40 \text{ equivalent weight NaOH}}{50 \text{ equivalent weight CaCO}_3} \\ &= 1.63 \frac{\text{pounds of 100 percent NaOH}}{1000 \text{ gallons potable water}} \end{aligned}$$

Summary of Cost per 1000 Gallons of Potable Water

Cation exchange acid usage = 1.34 pounds x 3.0 cents = 4.02 cents

Waste acid = 2.01 pounds x 3.0 cents = 6.0 cents

Neutralization NaOH = 1.63 pounds x 10 cents = 16.3 cents

These chemical costs and water quantities can now be used for life cycle costing of the system.

The ion-exchange equipment size and cost will vary with the cation-exchange flow rate and loading.

The traded water quantities are:

Potable water requirement 450,000 gallons per day

With 5 pounds/cubic foot regeneration, 38 percent of the potable water is treated by ion exchange
= 171,000 gallons per day.

With 3 pounds/cubic foot regeneration, 40.9 percent of the potable water is treated by ion exchange
= 184,050 gallons per day.

Figures A-20 and A-21 show the plan view of two cation exchangers and a degasifier, respectively, similar to the equipment that will be necessary for such an ion-exchange system.

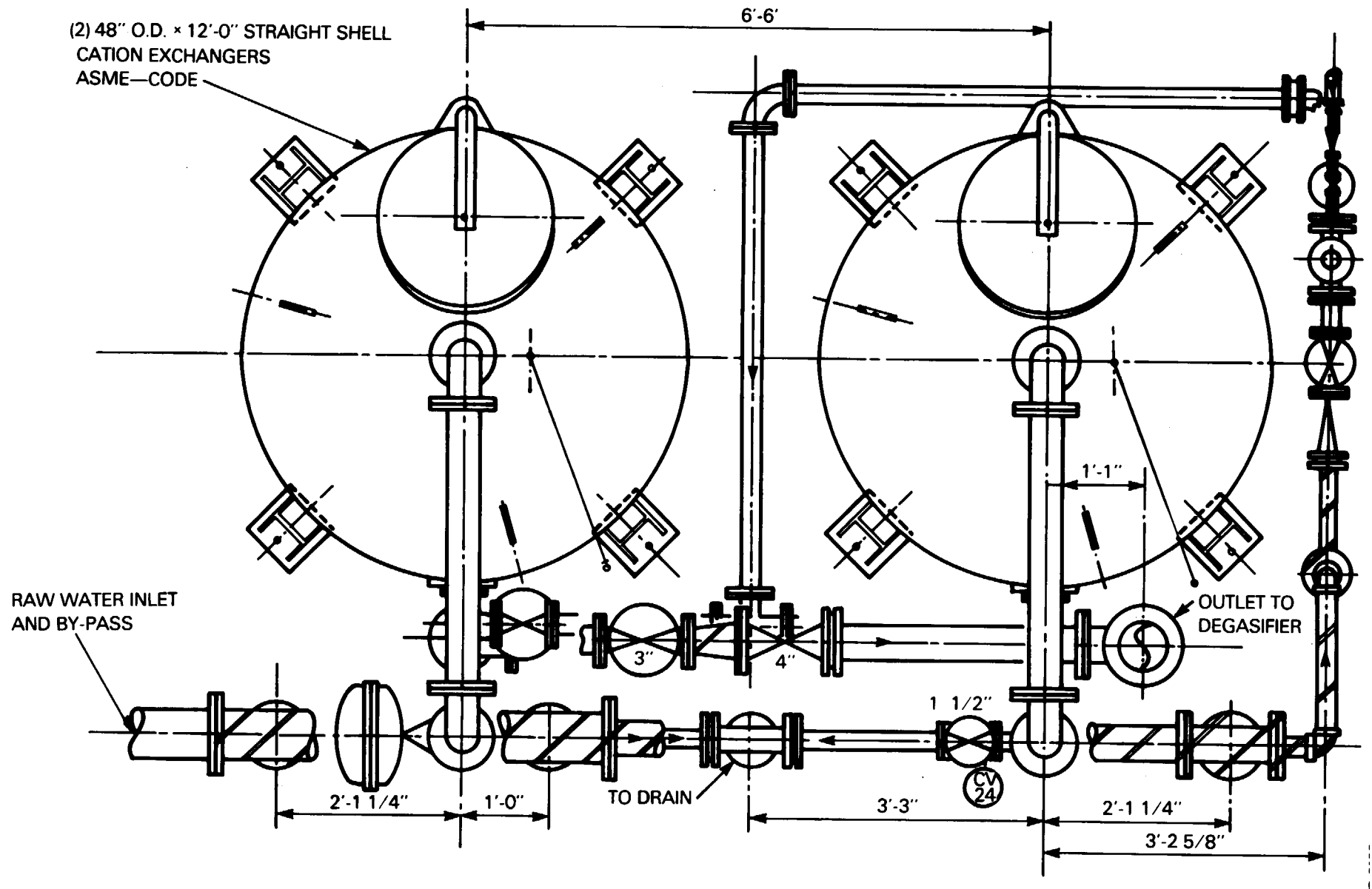
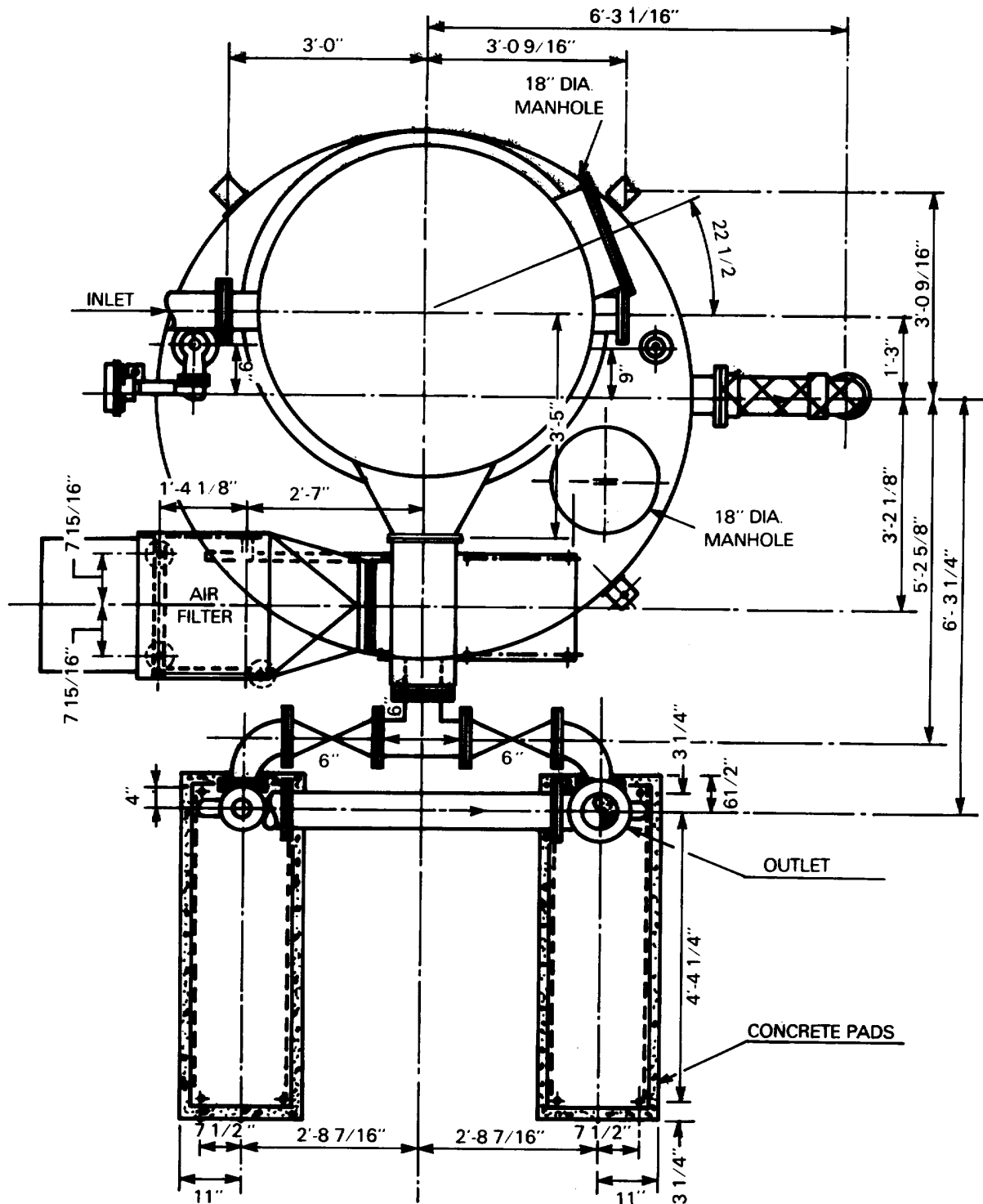


Figure A-20. Cation exchangers plan



Source: Hungerford & Terry, Inc.

Figure A-21. Degasifier and clearwell plan.

A-5. Sample of multiple component water blend optimization. A base on a volcanic island in the Pacific is to be expanded. While inadequate disinfection has often been blamed for the maladies of newcomers, the analysis requested before pumping and drilling tests are continued indicate a hard, high total dissolved solids, sulfate-rich fresh water lens on the island. For these reasons you have been assigned to direct a study to evaluate the various desalination options. You have good reason to believe that both water quantity and brine disposal will prevent the simple desalination of island well water to supply the projected 500 gallons per minute of potable water. A product-staged or double-pass reverse osmosis sea water desalination facility will apparently be required.

Symbols: x = The flow rate of fully treated relatively pure second-stage reverse osmosis product water used in the blend.
 y = The flow rate of the first-stage reverse osmosis product water used to blend.
 z = The flow rate of island well water used to blend.
 C_x = The unit cost of second-stage reverse osmosis water (water x).
 C_y = The unit cost of first-stage reverse osmosis product water (water y).
 C_z = The unit cost of island well water (water z).
 C = The unit cost of final blended water.

SAMPLE PROBLEM ON BLENDING

Given: The high quality two-pass water (water x) contains:

50.0 mg Cl^- /liter
 1.2 mg SO_4^{2-} /liter
 and 95.5 mg TDS/liter

The single-pass water (water y) contains:

500 mg Cl^- /liter
 30 mg SO_4^{2-} /liter
 85 mg TDS/liter

The well water presently being used (water z) contains:

30 mg Cl^- /liter
 400 mg SO_4^{2-} /liter
 729 mg TDS/liter

The final blend must meet TB MED 576 standards or

$\text{Cl}^- \leq 250$ mg Cl^- /liter
 $\text{SO}_4^{2-} \leq 250$ mg SO_4^{2-} /liter
 $\text{TDS} \leq 500$ mg TDS/liter

$i=n$

$\sum_{i=1}^n \text{Flow}_i \text{Concentration}_i \div \text{Flow Total} = \text{Final Concentration}$
 $i=1$

$\sum_{i=1}^n \text{Flow}_i \text{Cost}_i / \text{Gallon} \div \text{Flow Total} = \text{Final Unit Water Cost} = C$

Step 1: List Equations

a. Water Balance

$$x + y + z = 500$$

b. Blend Concentration Constraints

Chloride $50x + 500y + 30z \leq 500(250)$

Sulfate $1.2x + 30y + 400z \leq 500(250)$

Total Dissolved Solids

$$95.5 + 851y + 729z \leq 500(500)$$

c. Two-Way Blends

for Chloride

$$500y + 50x \leq 250(500)$$

$$x = 500 - y$$

$$\therefore 500y + 50(500) - 50y \leq 250(500)$$

$$\text{or } y \leq 500(250 - 50)/(500 - 50)$$

for Total Dissolved Solids

$$851y + 95.5x \leq 500(500)$$

$$x = 500 - y$$

$$\therefore 851y + 95.5(500) - 95.5y \leq 500(500)$$

$$\text{or } y \leq 500(500 - 95.5)/(851 - 95.5)$$

For sulfate, neither water y nor x are limited.

for Sulfate

$$400z + 1.2x \leq 250(500)$$

$$x = 500 - z$$

$$\therefore 400z + 1.2(500) - 1.2z \leq 250(500)$$

$$\text{or } z \leq 500(250 - 1.2)/400 - 1.2$$

for Total Dissolved Solids

$$792z + 95.5x \leq 500(500)$$

$$x = 500 - z$$

$$\therefore 792z + 95.5(500) - 95.5z \leq 500(500)$$

$$\text{or } z \leq 500(500 - 95.5)/(792 - 95.5)$$

For Chlorides, neither water x nor z are limited.

d. Cost

$$C_x x + C_y y + C_z z = C$$

Step 2: Project constraints onto water balance equation to eliminate one variable (preferably the most expensive water).

a. Chloride $50x + 500y + 30z \leq 125,000$

$$\underline{-50x - 50y - 50z = -25,000}$$

$$450y - 20z \leq 100,000$$

b. Sulfate $1.2x + 30y + 400z \leq 125,000$

$$\underline{-1.2x - 1.2y - 1.2z = -600}$$

$$28.8y + 398.8z \leq 124,400$$

c. Total Dissolved Solids $95.5x + 851y + 729z \leq 250,000$

$$\underline{-95.5x - 95.5y - 95.5z = -47,750}$$

$$755.5y + 633.5z \leq 202,250$$

Step 3: Graph resulting constraint questions, two dimensions at a time in the M dimensional space required (i.e., for blending 10 waters, all combinations of 9 things taken two at a time; for this example of 3 waters all combinations of 2 things taken two at a time). See figure A-22.

Step 4: Solve all constraints simultaneously to identify corners and edges. The most economical blend will almost always occur at a corner, but it is possible that an entire range of blend values along a constraint edge will be equally economical.

a. Chloride - Sulfate Pair

$$\text{SO}_4^{2-} = 28.8y + 398.8z \leq 124,400$$

$$\underline{(398.8/20)\text{Cl}^- = 8973.0y - 398.8z \leq 1,994,000}$$

$$9001.8y \leq 118,400$$

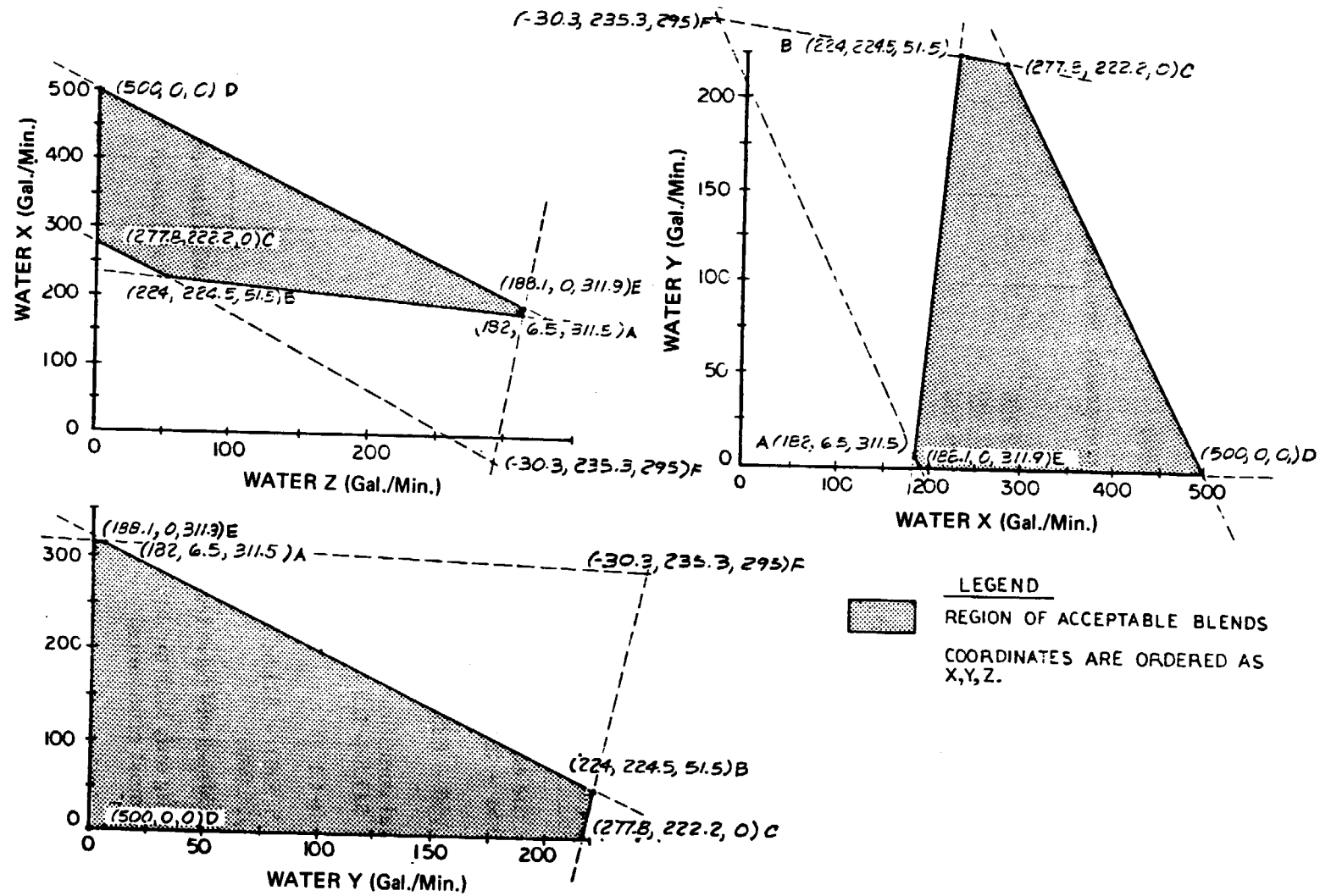


Figure A-22. Three projections of the water blends that satisfy TB MED 576 Requirements.

$$y \leq 235.3$$

$$z \leq [124,400 - 28.8(235.3)]/398.8$$

$$z \leq 295$$

$$x \leq 500 - 235.3 - 295 = -30.3$$

but the Total Dissolved Solids in this corner is:

$$-30.3(95.5) + 235.3(851) + 295(729) \leq 250,000$$

$$412,401.65 \leq 250,000$$

Therefore, this corner is outside of the TDS constraint. See figure A-22 point F.

b. Total Dissolved Solids - Chloride Pair

$$\text{Total Dissolved Solids } 755.5y + 633.5z \leq 202,250$$

$$(633.5/20)\text{Cl}^- = 14,253.75y - 633.5z \leq 3,167,500$$

$$15,009.25y \leq 3,369,750$$

$$y \leq 224.5$$

$$z \leq [202,250 - 755.5(224.5)]/633.5$$

$$z \leq 51.5$$

$$x \leq 500 - 224.5 - 51.5 = 224$$

and for Sulfate $\text{SO}_4^{=}$;

$$224(1.2) + 224.5(30) + 51.5(400) \leq 125,000$$

$$27,603.8 \leq 125,000$$

Therefore, this blend will have less than the maximum allowable sulfate concentration.

c. Total Dissolved Solids - Sulfate Pair

$$\text{Total Dissolved Solids } 755.5y \leq 202,250 - 633.5z$$

$$(755.5/28.8)\text{SO}_4^{=}= -755.5y \leq 3,263,340.3 - 10,461.6z$$

\therefore solving for the equal condition only

$$202,250 - 633.5z = 3,263,340.3 - 10,461.6z$$

$$z = 311.5$$

$$y \leq [202,250 - 633.5(311.5)]/755.5$$

$$y \leq 6.5$$

using the equal condition makes $z \leq 311.5$

$$x \geq 500 - 311.5 - 6.5 = 182$$

and for chloride Cl^-

$$182(50.0) + 6.5(500) + 311.5(30) \leq 125,000$$

$$21,695 \leq 125,000$$

Therefore, this blend will have less than the maximum allowable chloride Cl^- concentration.

Blends containing only high quality second-stage product water and one of the remaining waters x or y could be most economical.

d. Well Water z and Water x

1. Sulfate limited

$$z \leq 500(250 - 1.2)/(400 - 1.2)$$

$$z \leq 311.9 \text{ so } x \geq 188.1$$

2. TDS limited

$$z \leq 500(500 - 95.5)/729 - 95.5)$$

$$z \leq 319.25 \text{ so } x \geq 180.75$$

3. Chloride cannot limit since both have chlorides below 250.

e. Single-Pass Reverse Osmosis Water y and Water x.

1. Chloride limited

$$y \leq 500 (250 - 50.0)/(500 - 50.0)$$

$$y \leq 222.2 \text{ so } x \geq 277.8$$

2. TDS limited

$$y \leq 500(500 - 95.5)/(851 - 95.5)$$

$$y \leq 267.7 \text{ so } x \geq 232.3$$

3. Sulfate cannot limit since both waters have sulfates below 250. (The intercept at 4319.4 would require a removal flow of -3819.4 of second-stage product water x to concentrate the split stream to 250 mg SO₄/liter.)

f. Locate Inside Intercepts

1. Since $311.9 \leq 319.25$,

Sulfate limits use of water

$$z \text{ to } z \leq 311.9 \text{ with}$$

$$x \geq 188.1$$

2. Since $222.2 \leq 267.7$,

Chloride limits use of water

$$y \text{ to } y \leq 222.2 \text{ with}$$

$$x \geq 277.8$$

Step 5: Identify the coordinates of the corners of the convex polyhedron of acceptable blends.

In this case, the polyhedron is a pentagon with 5 corners.

The coordinates of the corners of acceptability are:

	x	y	z
1-	500	0	0
2-	577.8	222.2	0
3-	188.1	0	311.9
4-	182	6.5	311.5
5-	224	224.5	51.5

Step 6: Use Cost Equation to make each corner and edge a minimum cost solution (use the graph to identify adjacent corners).

a. All Second-Stage Product (No Blending)

$$Cx \ 500 \leq 188.1 \ Cx + 311.9 \ Cz$$

$$\text{and } Cx \ 500 \leq 277.8 \ Cx + 222.2 \ Cy$$

Therefore, don't blend at all if $Cx \leq Cz$ and $Cx \leq Cy$

b. Blend of x and y Waters Only

$$500Cx \geq 222.2 \ Cx + 277.8 \ Cy \text{ and } 222.2 \ Cx + 277.8 \ Cy \leq 224 \ Cx + 224.5 \ Cy + 51.5 \ Cz$$

$$\text{or } Cx \geq Cy$$

$$\text{and } 53.8 \ Cx \leq 2.3 \ Cy + 51.5 \ Cz$$

$$\text{or } Cx \leq 0.0427 \ Cy + 0.95725 \ Cz$$

Therefore, if the cost of water x was greater than the cost of water y, and less than $0.0427 \ Cy + 0.957 \ Cz$ then the blend of single- and double-pass sea water reverse osmosis products would be more economical than any blend containing well water.

c. Blend of x and z Water Only

$$500 \ Cx \geq 188.1 \ Cx + 311.9 \ Cz \text{ and } 188.1 \ Cx + 311.9 \ Cz \leq 182 \ Cx + 6.5 \ Cy + 311.5 \ Cz$$

$$\text{or } Cx \geq Cz$$

$$\text{and } 6.1 \ Cx + .4 \ Cz \leq 6.5 \ Cy$$

$$\text{or } Cx \leq 1.066 \ Cy - 0.066 \ Cz$$

Therefore, if the cost of water x was greater than the cost of water z, but less than $1.066 \ Cy - 0.066 \ Cz$, then the blend of well water and double-pass sea water reverse osmosis product would be more economical than any blend containing any single-pass waters.

d. Blend at Point A Figure A-22 containing a small amount of single-pass reverse osmosis water y.

$$182 C_x + 6.5 C_y + 311.5 C_z \leq 224 C_x + 224.5 C_y + 51.5 C_z \text{ and } 182 C_x + 6.5 C_y + 311.5 C_z \leq 188.1 C_x + 311.9 C_z$$

or

$$260 C_z \leq 42 C_x + 218 C_y$$

and $0.4 C_z \geq 6.5 C_y - 6.1 C_x$

or

$$16.25 C_y - 15.25 C_x \leq C_z \leq 0.1615 C_x + 0.838 C_y$$

Therefore, if the cost of well water is less than $0.1615 C_x + 0.838 C_y$ and greater than $16.25 C_y - 15.25 C_x$, then the use of 6.5 gallons/minute of first-stage reverse osmosis product water in a blend to reduce the amount of second-stage product needed, to dilute well water, from 188.1 gallons/minute to 182 gallons/minute will be economical.

e. Blending at Point B Figure A-22

using 224 gallons/minute of water x

224.5 gallons/minute of water y

and 51.5 gallons/minute of water x

$$224 C_x + 224.5 C_y + 51.5 C_z \leq 182 C_x + 6.5 C_y + 311.5 C_z, \text{ and } 224 C_x + 224.5 C_y + 51.5 C_z \leq 277.8 C_x + 222.2 C_y$$

or

$$42 C_x + 218 C_y \leq 260 C_z$$

$$\text{and } 51.5 C_z \leq 53.8 C_x - 23 C_y$$

or

$$0.1615 C_x + 0.838 C_y \leq C_z$$

$$\text{and } C_z \leq 1.0447 C_x - 0.0447 C_y$$

Therefore, if the cost of well water is greater than $0.1615 C_x + 0.838 C_y$ and less than $1.0447 C_x - 0.0447 C_y$, then the use of a blend of 51.5 gallons/minute of product-staged double-pass reverse osmosis water, with 224.5 gallons/minute of first-pass reverse osmosis product water and 224 gallons/minute of well water, would be the most economical blend.

Step 7: Make Reasonable Assumptions and Worst Case Scenarios

- The cost of second-stage reverse osmosis product water must be greater than the cost of first-stage reverse osmosis product water, because second-stage water is made from first-stage water.
- The maximum recovery available with most triple-reject-staged reverse osmosis membrane module assemblies is 85%.
- The second-stage low-pressure desalination of first-stage product water is almost always less expensive than the initial first-stage desalination of sea water.
- The expansion of a drain field collection or a well field system is almost always cheaper than the desalination of even brackish water.

Step 8: Put Assumptions and Scenarios into Mathematical Form

- Using 2 from step 7
 $C_x > C_y$
- Using a and b from step 7
 $C_x \geq 1/.85 C_y = 1.176 C_y$
- Using c and a from step 7
 $C_x \leq 2 C_y$ usually
- Using d from step 7
 $C_2 \leq C_y$ usually
- Using a and d above
 $C_x > C_y \geq C_z$ usually
- Using c and d above
 $1/2 C_x \leq C_y \leq C_z$ usually
- Using b and d above
 $.85 C_x > C_y \geq C_z$ usually

- Step 9: Analyze the Minimum Corner and Edge Constraints Solutions from Step 6 with respect to the assumptions and scenarios in Step 8.
- Since $C_x > C_y$ and for the minimum cost solution to be all double-pass water such as Case a, Step 6, $C_x > C_y$, blending should be done for economy.
 - When water x and y are the only components of a blend Case B, Step 6 shows
 $C_x \leq 0.0427 C_y + .957 C_z$
 and Step 8, Case g shows
 $.85 C_x > C_y \geq C_z$
 Therefore, $1.176 C_y \leq 0.0427 C_y + .957 C_z$
 or $1.134 C_y < C_z$,
 which violates the second half of Step 8, Case g, unless the cost of well water really is greater than 1.13 times the cost of first-stage reverse osmosis sea water desalination.
 - When water x and z are the only components of a blend Case C, Step 6 shows
 $C_x \leq 1.066 C_y - 0.066 C_z$
 and Step 8, Case b shows
 $C_x > 1.176 C_y$
 Therefore, $1.176 C_y < 1.066 C_y - 0.066 C_z$
 or $0.11 C_y \leq -0.066 C_z$,
 so this cannot be an optimum solution unless someone is paying you to dispose of well water z.
 - When 6.5 gallons/minute of first-stage reverse osmosis product water is used in a triple blend Step 6, Case d shows
 $16.25 C_y - 15.25 C_x \leq C_z \leq 0.1615 C_x + 0.838 C_y$
 and Step 8, Case f shows
 $.5 C_x \leq C_y \geq C_z$ usually
 Therefore,
 $16.25 C_y - 15.25(2 C_y) \leq C_z \leq 0.1615(2 C_y) + 0.838 C_y$
 or $-14.25 C_y \leq C_z \leq 1.161 C_y$,
 so for any cost from being paid 14.25 times the cost of water y to dispose of well water z to having water z cost 1.161 times water y the optimum cost solution will be this triple blend.
 - When the acceptable triple blend of
 224 gallons/minute of water x
 224.5 gallons/minute of water y
 and 51.5 gallons/minute of water z
 is most economical, Step 6, Case e shows
 $0.1615 C_x + 0.838 C_y \leq C_z \leq 1.0447 C_x - 0.0447 C_y$
 and Step 8, Case f, shows
 $.5 C_x \leq C_y \geq C_z$ usually
 and Step 8, Case g shows
 $.85 C_x \geq C_y \geq C_z$ usually
 Therefore,
 $(0.1615)(1.176 C_y) + 0.838 C_y \leq C_z \leq 1.0447 (2 C_y) - 0.0447 C_y$
 $1.0279 C_y \leq C_z \leq 2.0447 C_y$
 so this blend will be economical only if the cost of well water is greater than the cost of single-pass desalinated sea water by more than 1.03 times and less than 2.04 times as expensive as single-pass desalinated sea water. These conditions violate the second part of Step 8, Cases f and g.

Step 10: Draw Conclusions

- The most economical blending strategy on the island will almost certainly be: 182 gallons/minute of high quality second-stage, product-staged reverse osmosis desalinated sea water

6.5 gallons/minute of high chloride high total dissolved solids single-or first-stage reverse osmosis desalinated sea water. 311.5 gallons/minute of high sulfate island well water

This blend will be most economical when:

1. The cost of island well water is between 14.25 times single-or first-stage product water and 1.161 times the cost of this first-stage product water.
2. The removal of 311.5 gallons/minute of well water does not degrade the water quality in the wells.
- b. The availability of up to 312 gallons/minute of island well water and the quality of island well water should be investigated extensively.
- c. If over roughly $(500) + 85 = 600$ gallons/minute of island well water can easily be withdrawn without degrading the quality or quantity of island well water in the future, then the facility should be reviewed again for the installation of electrodialysis-reversal treatment at 85% recovery and disposal of the resulting high sulfate brine.
- d. The use of a mere 6.5 gallons/minute of first-stage desalinated sea water will save at least $(188.1 - 182)$ gallons/minute = 6.1 gallons/minute of second-stage reverse osmosis water plus $(6.1) + 0.85 \times 6.5$ gallons/minute = 0.68 gallons/minute first-stage reverse osmosis water. This savings is definitely worth the engineering, construction, and operation costs.
- e. A table showing the final cost of blended waters consisting of the five possible minimum cost blends of \$.10 well water, \$4.00 single-pass reverse osmosis water, and \$5.75 double-pass reverse osmosis water has been prepared and is shown in table A-3. Figure A-23 shows a plan view of the desalination system of a two pass reverse osmosis system.

A-6. Sample problem for simple blend. A base in the desert has a water with a total dissolved solids content of 907 mg TDS/liter. If reverse osmosis is to be used as a desalination technique in this application, then the final product water will have far less than the required 500 mg TDS/liter. If 250,000 gallons/day of finished water will be required, how much of the raw water can be rebled in meeting TB-MED 576 requirements?

Symbols:

x = Amount of water that must be treated

Given:

Daily flow is 250,000 gallons/day

Finished blend concentration is 500 mg TDS/liter.

Initial feed concentration is 907 mg TDS/liter.

$$\text{Flow Concentrated} = \frac{(\text{Desired Concentration} - \text{Dilute Concentration}) \text{Flow Dilute}}{(\text{High Concentration} - \text{Desired Concentration})}$$

SAMPLE PROBLEM FOR SIMPLE BLEND

Assumptions: a. The total dissolved solids rejection of a low-pressure membrane is about 90%, leaving .1 x TDS in the dilute water stream.

b. Total dissolved solids are the limiting factors in the rebinding.

Therefore: The flow of raw undesalinated water used = 250,000 gallons/day - x

And:

$$(250,000 \text{ gallons/day} - x) = \frac{[500 - .1(907)]x}{(907 - 500)}$$

$$250,000 \text{ gallons/day} = x + (409.3/407)x$$

$$250,000 \text{ gallons/day} = 2.00565x$$

$$\therefore x = 124,000 \text{ gallons/day}$$

A-7. Silt density index (SDI). This fouling index mentioned in Chapter 3, tables 4-2 and 4-3, and Chapter 5 is measured on a 47-millimeter-diameter 0.45-micron pore size membrane filter. The data used by the manufacturers to calculate the index are the time (T1) necessary initially to force 500 milliliters of solution through a clean 0.45-micron filter with a 30-pound-per-square-inch pressure differential across the filter, followed by the time (T2) required to force an additional 500

Well Water Z Unit Cost = \$0.10/Gallon		Single-Pass R.O. Water Y Must Be Produced for X-0 Unit Cost = \$4.00/Gallon		Double-Pass R.O. Water X Used to Blend to Quality Unit Cost = \$5.75/Gallon		TOTAL Blended Water		
Flow of Water Z	Cost Incurred for Water Z	Flow of Water Y	Cost Incurred for Water Y	Flow of Water X	Cost Incurred for Water X	Total Cost Per/Hr	Total Flow Per/Hr	Unit Cost of Water
In Gallons/Min	In \$/Min	In Gallons/Min	In \$/Min	In Gallons/Min	In \$/Min	In \$/Min	In Gallons/Min	
0	\$ 0.00	0	\$ 0.00	500	\$2875.00	\$2875.00	500	\$5.75
0	\$ 0.00	222.2	\$888.80	277.8	\$1597.35	\$2486.15	500	\$4.97
311.9	\$31.19	0	\$ 0.00	188.1	\$1081.58	\$1112.77	500	\$2.23
311.5	\$31.15	6.5	\$ 26.00	182	\$1046.50	\$1103.65	500	\$2.21
51.5	\$51.50	224.5	\$898.00	224	\$1288.00	\$2237.50	500	\$4.48
Put	C _x = \$5.75/Gallon C _y = \$4.00/Gallon C _z = \$0.10/Gallon			In Given:				

Table A-3. Cost projections for possible optimum blends.

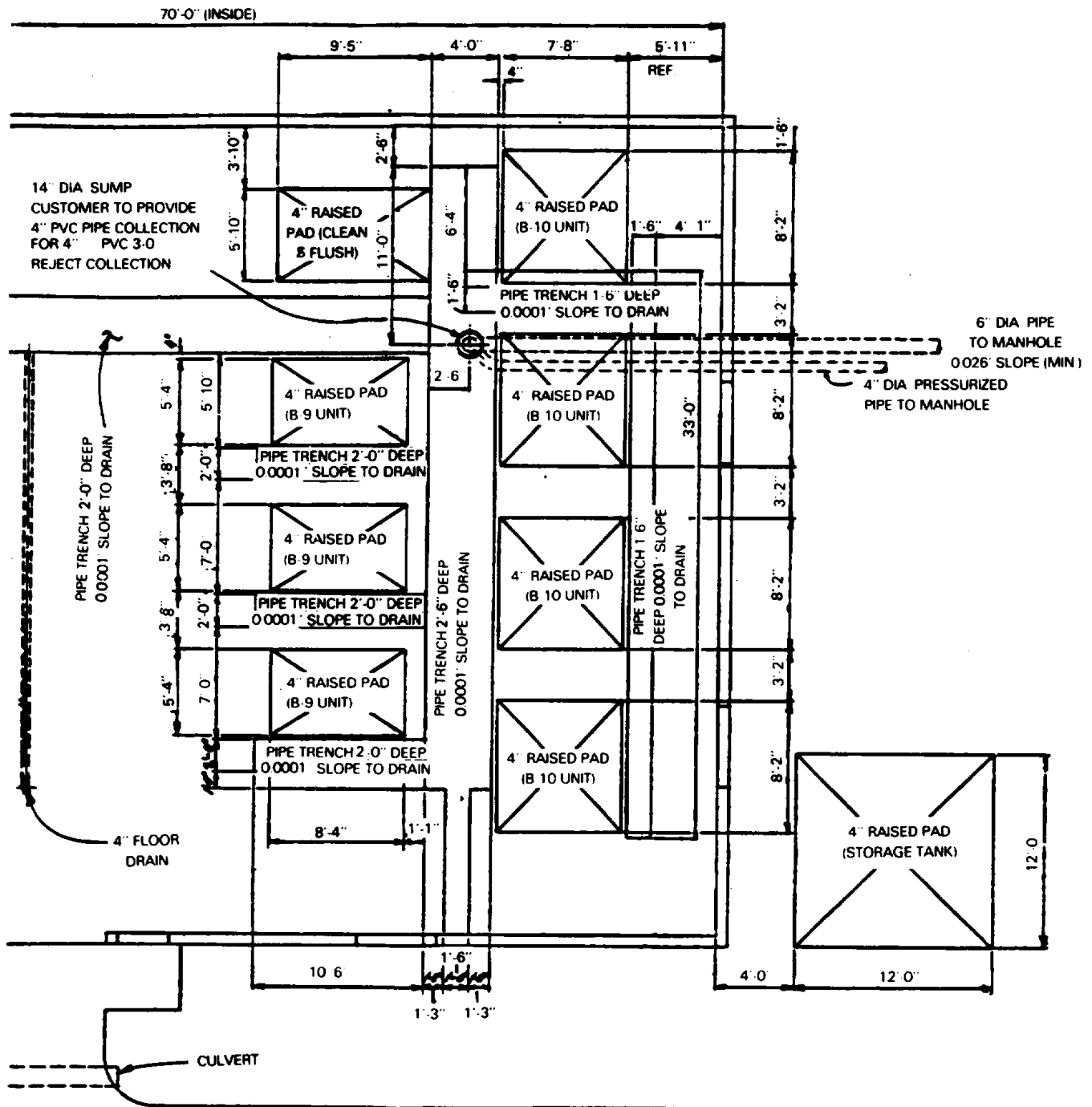


Figure A-23. Plan review of a two-pass reverse osmosis system.

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milliliters of solution through the same filter (operating at the constant pressure 30 pounds per square inch gauge) 15 minutes later. Between these two time periods ($T_B = 15$ minutes) the solution must be continuously fed to the membrane filter under a constant 30-pound-per-square-inch gauge pressure differential. The silt density index is then calculated in the following manner:

Symbols:

T_1 = Time for first 0.132 gallons to pass filter

T_B = Time between two measured 500-milliliter samples, usually 15 minutes

T_2 = Time for second 500-milliliter sample to pass filter

SDI = Silt Density Index

Given:

$$T = 1 \text{ minute}$$

$$T_B = 15 \text{ minutes}$$

$$T_2 = 4.083 \text{ minutes}$$

$$\frac{(1 - T_1/T_2) \times 100}{T_B} = \text{SDI}$$

The formula for the SDI is as follows:

$$\text{SDI} = (1 - 1 \text{ minute}/4.083 \text{ minutes}) 100/15 \text{ minutes} = 5.03 \text{ silt density index}$$

A-8. Concentration factor. If the percentage of the feed stream that is removed as product water (i.e., percent recovery) is known, the concentration of the brine can be calculated for the purpose of estimating scaling concentrations as follows:

Symbols:

$$\text{Percent Rec.} = 100 \times \text{the fraction of the feed water that becomes product water}$$

Given:

$$30 \text{ percent of the feed water becomes product}$$

$$\text{At 30 percent recovery, 70 percent of water contains all the original salt, } \therefore$$

$$1/0.7 \times \text{original concentration} = \text{final concentration}$$

$$\frac{1}{1 - \frac{\text{Percent Rec.}}{100}} = \text{Concentration factor}$$

$$\frac{1}{1 - \frac{30}{100}} = 1.429$$

A-9. Reverse osmosis membrane requirement (manufacturers will supply the necessary number of permeators).

The following equations can be used with membrane manufacturer's water flux constants to calculate a water flux or, by rearrangement of the equation, a membrane area requirement can be calculated.

Symbols:

$$Q_w = \text{Water flow}$$

$$K_w = \text{Water flux constant for the membrane}$$

$$A = \text{Area of membrane}$$

$$\Delta P = \text{The pressure drop across the membrane (not including head losses to or from the membrane)}$$

$$A\pi = \text{The osmotic pressure difference across the membrane}$$

$$\text{Usually about: } \frac{10 \text{ pounds per square inch}}{1,000 \text{ milligrams per liter of total dissolved solids}}$$

Given:

$$K_w = 2.53 \times 10^{-7} \text{ gallons/pound-hour}$$

$$\text{The membrane area, } A = 1,000 \text{ square feet}$$

$$\text{The applied pressure, } P = 900 \text{ pounds/square inch}$$

$$\text{The osmotic-pressure difference, } \Delta\pi = 350 \text{ pounds/square inch.}$$

$$Q_w = K_w A (\Delta P - \Delta\pi)$$

$$Q_w = 2.53 \times 10^{-7} \text{ gallons/pound-hour} \times 1,000 \text{ square feet} \times 144 \text{ square feet} \times (900 \text{ pounds/square inch} - 350 \text{ pounds/square inch})$$

$$Q_w = 20 \text{ gallons/hour}$$

A-10. Reverse osmosis membrane salt flux (manufacturers will meet desired water quality). The following calculations can be used with membrane manufacturer's specific ion flux constants to estimate the concentrations of particular ions in the product water.

Symbols:

Q_s	= The salt flow
K_s	= The salt flux constant for the ion under consideration across the membrane
A	= The area of membrane
$C_{ion} \text{ feed/brine average}$	= One half the sum of the feed concentration and the reject brine concentration of the ion under consideration (Mg^{++} in this example)
$C_{ion} \text{ product}$	= The concentration in the product of the ion under consideration (Mg^{++} in this example)

Given:

The salt flux constant for this membrane $K_s = 2.8 \times 10^{-4}$ gallons per square foot-hour

The membrane area $A = 1,000$ square feet

The feed water contains 204.4 grains per gallon of magnesium Mg^{++} .

The product water contains 0.3 grains per gallon of magnesium Mg^{++} .

$Q_s = K_s A (C_{ion} \text{ feed/brine average} - C_{ion} \text{ product})$

$Q_s = (2.8 \times 10^{-4} \text{ gallons per square foot-hour})$

$(1,000 \text{ square feet})$

$(204.4 \text{ grains per gallon } Mg^{++} - 0.3 \text{ grains per gallon } Mg^{++})$

$= 57 \text{ grains } Mg^{++} \text{ per hour}$

A-11. Second-law limiting thermal efficiency. A perfect conversion of heat into work is not possible. There is, however, a limiting efficiency of conversion of heat energy to mechanical or electrical energy. No heat machine can operate at this best efficiency, but it does allow a rough estimate of the value of lower grades of steam.

Symbols:

$T_H =$ Temperature in degrees Rankine of steam source. Higher temperature in degrees Rankine (degrees Rankine equal degrees Fahrenheit plus 460 degrees)

$T_L =$ Temperature in degrees Rankine of the cooling sink. Lower or discharge temperature in degrees Fahrenheit

$e_{max} =$ Maximum possible second law efficiency (maximum percent of the heat available that can be converted theoretically into work)

$e_{max} = (T_H - T_L)/T_H \times 100$

Given:

The steam temperature drop available is 264 degrees Fahrenheit to 68 degrees Fahrenheit. (See problem A-2.)

$e_{max} = (724 \text{ degrees Rankine} - 528 \text{ degrees Rankine})/724 \text{ degrees Rankine} \times 100$

$e_{max} = 27 \text{ percent}$